

The standardization of major Well-to-Wheel models: Measuring uncertainty on a macro level

by

HASSAN M. EL-HOUJEIRI
B.Sc. (American University of Beirut – Lebanon) 2004
M.Sc. (University of Warwick – UK) 2006

THESIS

Submitted in fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

ENGINEERING SCIENCE

in the

DEPARTMENT OF ENGINEERING SCIENCE

of the

UNIVERSITY OF OXFORD

SUPERVISOR:
Dr. Robert Field

January 2011

Copyright ©

Hassan M. El-Houjeiri

2011

DEDICATION

This thesis is dedicated to my parents

Dr. Massoud and Mrs. Elham El-Houjeiri

who brought me to this World and surrounded me with
their love and endless support.

ACKNOWLEDGEMENT

I am heartily thankful to my supervisor, Dr. Robert Field, FIChemE, CEng, PhD (Cantab), MA, MEng (Hons), Department of Engineering Science and Fellow of Balliol College, University of Oxford. His encouragement, guidance and support from the initial to the final level have provided a good basis for the present thesis.

I wish to extend my warmest thanks to all those who have helped me with my work in the Department of Engineering Science and Balliol College.

I owe my loving thanks to my wife, Rabia, and my parents. They have lost a lot due to my research abroad. Without their encouragement and understanding it would have been impossible for me to finish this work. My special gratitude is due to my uncle, Najib, my sister, Rana, and my brother, Hussein, for their loving and support.

The financial support of the National Council of Scientific Research, Lebanon, and the Arab British Chamber of Commerce, U.K., is gratefully acknowledged.

Oxford, England, January 2011

Hassan M. El-Houjeiri

ABSTRACT

The standardization of major Well-to-Wheel models: Measuring uncertainty on a macro level

Hassan M. El-Houjeiri

Balliol College

D.Phil. in Engineering Science

Michaelmas Term 2010

This project concentrated upon the development of the Standardization Transport Model (STM) by assembling the largest possible assessment platform. It combines data from all of the major Well-to-Wheel (WtW) models in the field. The STM was developed for each chain under study by formulating the data in the major databases so that the Well-to-Tank processes covered Feedstock Production, Feedstock Transport, Fuel Production and Fuel Distribution. With the addition of Tank-to-Wheel data, a comprehensive STM was obtained for each chain. For each stage there is a range of values that was characterized by a probability distribution and through the use of Monte Carlo simulation the distribution was sampled and overall values for the total energy consumption, in MJ/km, and total GHG emissions in grams of carbon dioxide equivalent per kilometre (gCO_2eq/km) were generated. By statistical means these distributions were compared to assess the risk of debt as well as the likelihood of major savings if they were to be implemented. The scope of the analysis was limited to passenger cars transport and does not include other forms of road transport.

Major classic WtW models may account for subjective uncertainty in the input parameters of the model but with a default set of inputs which represents only one database and one set of modelling assumptions and choices. This individualism and determinism in the WtW modelling nowadays explains the significant discrepancies that arise across the results from different models. The level of variation presented poses a major problem in the context of policy making and strategic planning. The generation of the STM rests upon the convection that a synthesis which generates a statistically relevant aggregate of the different WtW results from the different models of the major expert groups would eliminate the present inconsistencies and deliver the reliability required for making robust strategic decisions.

Advantage was taken of the richness of the STM outputs to assess the sensitivity of the results and identify the major factors of disagreement within the expert systems. Here the STM presents the largest platform of comparison and the most comprehensive evaluation of the different WtW models in the field. The provision of such a sensitivity analysis was not possible without allowing for variation in the elements of the model as done using the STM. Secondly, the key outputs of the model were compared under the criterion of sustainability from both energy and environmental perspectives. This was done by the synthesis of a first-of-its-kind distribution of the difference between the conventional system and the alternative system for each option under study. The output reflects as complete a population as possible of what may occur in reality in terms of direct impact on sustainability. This method of comparison was not possible without synthesizing an aggregate of possibilities as done using the STM. Thirdly, synergies with the

power sector were studied to identify which strategies delay the global reduction in GHG emissions and which are to be preferred from an overall perspective. Here the author lead the transport research community in looking on the global benefits of alternative transport systems, rather than only looking through the window of the transport sector, by redrawing the boundary for the analysis of prospective transport systems. Last and not least, the outcomes of the comparative analyses of the STM results were aggregated into a proposed strategic framework for carbon and energy reduction in passenger cars transport. The strategic framework is placed into perspective by building a set of future scenarios and scaling the effect for the progressive implementation of these scenarios and making a comparison with the business-as-usual forecast.

The creation of an energy economy based on hydrogen fuel was found to be a highly questionable objective because electrically driven vehicles are superior with regard to systems that are either nuclear resourced or based on non-biomass renewables. For hydrogen, only the option from waste wood via gasification was found to be very attractive. However because only a minor role for hydrogen is foreseen, it is envisaged that the development of a hydrogen infrastructure would not be feasible. Therefore the use of hydrogen will be constrained to decentral systems or central systems with liquid hydrogen distribution. With regard to cultivated biomass, the sugar ethanol options are the best in terms of land use with sugarcane having the advantage of being economic and available for short-term penetration. The safe implementation of sugar ethanol, which includes avoidance of CO_2 emissions from indirect land use change and low fertilizers use, guarantees significant savings and have a good potential for large CO_2 emissions savings. Generally due to land use limitation cultivated biomass based options cannot be sustained on the long term. Last and not least, the CO_2 emissions savings from clean coal technology is questionable without CCS technology and even though with the implementation of CCS no significant savings are certain.

On the other hand, besides the transport sector the power sector is another major sector of energy resource consumption and careful consideration of any synergies between the sectors is essential for the completeness of the analysis. The strategy in which the use of alternatives such as NG, nuclear and renewables is not diversified but fed only into the power sector is to be preferred as this avoids possible CO_2 emissions from indirect resource use change, and it also isolates the power market to maintain upstream energy security. Finally, the answer to whether it is still possible to save the World from the disastrous consequences of Global Warming is a preliminary “yes” but requires the development and implementation of a complete technology package including nuclear power which is widely debated at the present.

Table of Contents

ABSTRACT ..... **V**
Table of Appendices ..... **XIII**
List of Figures ..... **XIV**
List of Tables ..... **XIX**
Glossary of Terms ..... **XXI**
List of Nomenclature ..... **XXIII**
1 Introduction and Problem Context **1**
1.1 Research background 1
1.2 Thesis contribution in the context of energy research 2
1.2.1 The Standardization Transport Model (STM) 2
1.2.2 Nature of results from the STM 9
1.2.3 The uses of the STM 12
1.3 Literature review 12
1.3.1 Reference models 13
1.3.1.1 Argonne National Laboratory (ANL) 13
1.3.1.2 General Motors (GM) 14
1.3.1.3 European Commission (JRC), EUCAR and Concawe 15
1.3.1.4 University of California, Davis 15
1.3.1.5 The European Fuel Cell Forum 16
1.3.1.6 Öko-Institut (Institute for Applied Ecology) 17
1.3.2 Studies excluded 19
1.3.3 Important observations 20
1.4 Thesis structure 23
2 Goal, Scope and Methodology **26**
2.1 The Well-to-Wheel model 26
2.2 Goal definition 27
2.3 Scope of analysis 28
2.3.1 The structure of the STM 28
2.3.2 The transport scope of the STM 29
2.3.3 The boundary of the STM 29
2.3.4 Geographic scope and timeframe 31

2.3.5 Chains 31
2.4 The standardization process 40
2.4.1 The general components of a WtW model 41
2.4.1.1 Process structure 41
2.4.1.2 System structure 43
2.4.2 The structural differences between models 44
2.4.2.1 Basic structure 47
2.4.2.2 Semi-real structure 47
2.4.2.3 Real structure 49
2.4.3 The effect of variation in the modelling structure 49
2.4.4 The database structure and data transparency 52
2.4.4.1 GREET model 52
2.4.4.2 GM-LBST and JEC models 60
2.4.4.3 GEMIS model 65
2.4.4.4 LEM model 70
2.4.4.5 Ulf Bossel eco-efficiency model 72
2.4.4.6 The TtW data elements 73
2.4.4.6.1 Vehicle operation 73
2.4.4.6.2 Electric powertrain 74
2.5 Limitations 75
3 Statistical Methods 76
3.1 What is a model? 76
3.2 Types of WtW results 76
3.2.1 Sample space 76
3.2.2 The stability of a random measure 78
3.2.3 Comparison of different types of WtW results 81
3.3 The statistical map of the standardization process 83
3.3.1 Sampling the population 83
3.3.2 Characterizing the distributions 88
3.3.2.1 Data filter 88
3.3.2.2 Distribution fit 91
3.3.2.3 Fit statistics 94

3.3.3 Describing the relationships between variables....95
3.3.3.1 The principal relational element....96
3.3.3.2 Defining the correlation matrix....99
3.3.3.3 The correlation between the STM outputs....101
3.3.4 Running the simulation....102
3.3.4.1 Simulation....103
3.3.4.2 Monte Carlo simulation....103
3.3.4.3 Standard error....105
3.3.4.4 Sampling method....106
3.3.4.5 Simulation rules....110
3.3.5 Generating the simulation results....111
3.3.5.1 Uncertainty analysis....112
3.3.5.2 Sensitivity analysis....112
3.3.5.3 A possible question....116
3.4 Limitations....117
4 Results Analysis and Discussion I: Sensitivity Analysis....119
4.1 The probing of output uncertainty....119
4.1.1 The qualitative sensitivity analysis....119
4.1.2 The quantitative sensitivity analysis....121
4.2 Fuel chain (WtT)....121
4.2.1 Feedstock Production....121
4.2.1.1 Crude Oil....121
4.2.1.2 Natural gas....123
4.2.1.3 Coal....124
4.2.1.4 Biomass....126
4.2.1.4.1 Sugarcane....129
4.2.1.4.2 Sugarbeet....135
4.2.1.4.3 Farmed wood....137
4.2.1.4.4 Residual lingo-cellulosic biomass....138
4.2.1.4.5 Biomass for hydrogen fuel....140
4.2.1.5 No-biomass renewable resources....142
4.2.1.6 Uranium....145

4.2.2 Feedstock transport 146
4.2.3 Fuel production 148
4.2.3.1 Crude refining 149
4.2.3.2 Natural gas conversion 150
4.2.3.2.1 Natural gas to gaseous hydrogen in centralized SMR plant 151
4.2.3.2.2 Natural gas to gaseous hydrogen at refuelling stations 152
4.2.3.2.3 Natural gas to electricity 153
4.2.3.3 Conversion of non-biomass renewables 154
4.2.3.3.1 Hydrogen from central water electrolysis 154
4.2.3.3.2 Hydrogen from onsite water electrolysis 155
4.2.3.4 Biomass transformation 156
4.2.3.4.1 Fermentation 156
4.2.3.4.1.1 Cellulosic biomass 158
4.2.3.4.1.2 Sugar biomass 159
4.2.3.4.2 Gasification 161
4.2.3.5 Coal conversion to electricity 163
4.2.3.6 Uranium fuel conversion 165
4.2.3.6.1 Electricity from uranium fuel 165
4.2.3.6.2 Hydrogen from nuclear electricity 166
4.2.4 Fuel distribution 168
4.3 Vehicle operation (TtW) 171
4.4 The summary of the major sources of variability 172
5 Results Analysis and Discussion II: Uncertainty Analysis 177
5.1 The criteria of comparison 177
5.1.1 Comparison of chains based on exhaustible resources 177
5.1.2 Comparison of chains based on non-exhaustible resources 178
5.2 System optimization 179
5.3 NG-based chains 180
5.3.1 Energy consumption of NG options 180
5.3.2 Energy change distributions for the NG options 182
5.3.3 GHG emissions of NG options 185
5.4 Non-biomass renewables 186

5.4.1 An overview of the energy consumption 187
5.4.2 A closer look on energy consumption 188
5.4.3 GHG emissions of renewables based options 189
5.5 Nuclear-based chains 191
5.6 Coal-based chains 193
5.7 Biomass-based chains 196
5.7.1 Land use efficiency 196
5.7.2 Energy consumption of biomass options 199
5.7.3 GHG emissions of biomass options 201
5.8 Discussion and concluding remarks 205
5.8.1 General remarks 205
5.8.2 Optimising the use of Natural Gas 205
5.8.3 Comparison of hydrogen FCVs and BEVs 206
5.8.4 The potential role of biofuels 207
5.8.5 Final remarks 208
6 New Boundary for Transport Systems Analysis 210
6.1 Introduction 210
6.2 Synergies between power and transport 211
6.3 Scenarios 212
6.4 Methods 215
6.5 Results and discussion 219
6.6 Concluding remarks 222
7 Standard Results into Perspective 224
7.1 Introduction 224
7.2 Strategic framework 226
7.3 Methods 228
7.3.1 Historical data 228
7.3.2 Traffic forecast 228
7.4 Scenarios 230
7.4.1 Complete technology package 230
7.4.2 Nuclear free World 235
7.4.3 Renewables breakthrough only 236

7.4.4 Nuclear only 237
7.4.5 All technology except renewables breakthrough 238
7.4.6 All technology except CCS 239
7.5 The scale of effect 240
7.6 Conclusions 243
7.7 Limitations 244
8 Summary and Conclusions 246
8.1 Summary 246
8.2 Conclusions 248
8.2.1 Sensitivity analysis results 248
8.2.2 Comparative analysis results 249
8.2.3 Cross sectoral analysis 250
8.2.4 Framework analysis 251
References 252

Table of Appendices (Supplementary Data)

Appendix A: The data sets and calculations for Table 3.1 and Figure 3.1 .....
Appendix B: The calculation of the system assumptions for Figure 3.3 .....
Appendix C1: GREET model Well-to-Tank data inventory (before aggregation) .....
Appendix C2: GREET model Well-to-Tank data inventory (after aggregation) .....
Appendix D: JEC model Well-to-Tank data inventory .....
Appendix E: GM-LBST model Well-to-Tank data inventory .....
Appendix F: Bossel *et al.* (2003) eco-efficiency model Well-to-Tank data inventory .....
Appendix G: LEM Well-to-Tank data inventory .....
Appendix H: GEMIS Well-to-Tank data inventory .....
Appendix I: Miscellaneous Well-to-Tank data inventory .....
Appendix J: Tank-to-Wheel data inventory (per km output) .....
Appendix K: Tank-to-Wheel data inventory (per MJ_W output) .....
Appendix L: Inputs, correlations and outputs of Well-to-Tank models .....
Appendix M: Map of input data elements .....
Appendix N: Inputs of Tank-to-Wheel stages .....
Appendix O: Well-to-Wheel results .....
Appendix P: The calculation of correlations between Well-to-Wheel results .....
Appendix Q: Well-to-Wheel analysis: The calculation of change distributions .....
Appendix R: The statistics of input distributions .....
Appendix S: The statistics of output distributions .....
Appendix T: Results of sensitivity analysis .....
Appendix U: Scenarios of synergistic behaviour and calculations .....
Appendix V: UK passenger cars traffic forecast by StatTools .....
Appendix W: Framework scenarios and calculations .....

Soft documents (.xlsx files)

<u>Note:</u> Requests for a copy of the appendices will be considered by the author and his supervisor[1] acting jointly.

[1] Dr. Robert Field, University of Oxford, Department of Engineering Science, Parks Road, OX1 3PJ, U.K; Tel: +44(0)1865277720; Email: robert.field@eng.ox.ac.uk

List of Figures

Figure 1.1: A diagrammatic representation of different WtW chains (built for representative purposes from the pathways under consideration in the STM which are introduced in Chapter 2) 4
Figure 1.2: The roots of the STM output. Level 1 relates to target population. Level 2 is the sampled population used in the modelling. Level 3 is the set of modelling elements which describe the data elements of the sampled population. 10
Figure 2.1: The structure of the standardization transport model (STM) 28
Figure 2.2: The NG-based pathways under consideration 33
Figure 2.3: The biomass-based pathways under consideration 34
Figure 2.4: The non-biomass renewables-based pathways under consideration 35
Figure 2.5: The nuclear-based pathways under consideration 36
Figure 2.6: The crude-based pathways under consideration 37
Figure 2.7: The coal-based pathways under consideration 37
Figure 2.8: A simple flow diagram of the standardization process. The three steps marked with an asterisk (*) represent challenges that were addressed in the creation of the STM. 40
Figure 2.9: The energy components of a process 41
Figure 2.10: The general structure of a system model 43
Figure 2.11: A representation of a circular loop 44
Figure 2.12: The different modelling structures of various WtW models 46
Figure 2.13: A general representation of a system model based on (a) a realistic model on the left hand side, and (2) a simplified non-realistic model on the right hand side 51
Figure 2.14: A snapshot from the GREET model spreadsheet showing the energy consumption for each stage in the production and distribution of gaseous hydrogen 53
Figure 2.15: A snapshot from the GREET model spreadsheet showing the emissions for each stage in the production and distribution of gaseous hydrogen 54
Figure 2.16: The graphical representation of the algorithm for the aggregation of the GH2 T&D and compression processes based on the deduced modelling structure of the GREET model as presented in Figure 2.12 58
Figure 2.17: The input data of a large hydrogen steam reforming (SMR) plant from the GM-LBST full background report (GM et al., 2002a) and the Excel sheets of the JEC model (JRC et al., 2008a) 62
Figure 2.18: A snapshot from the JEC data appendices showing the most relevant form of data provided by the LBST tool based models (JRC et al., 2008b) 63
Figure 2.19: A snapshot from the STM input data sheets showing data that stem from the JEC database 65
Figure 2.20: A snapshot from Lopez et al. (2009) showing the GM-LBST data for diesel supply used in the cited study for the life cycle analysis of refuse trucks in the city of Madrid 65
Figure 2.21: (a) On the left hand side shows a NG pipeline transport process chain from GEMIS, and (b) on the right hand side shows the mechanical energy fuel cycle (Öko-Institut, 2008) 66

Figure 2.22: The modelling of the cumulative processes of a conventional gasoline WtT chain as predefined by GEMIS 67
Figure 2.23: Energy consumption for different hydrogen pathways (Bossel et al., 2003).....72
Figure 2.24: A simple energy flow diagram of the vehicle operation. Note there is no energy output.....74
Figure 2.25: The energy consumption distribution of electricity mains use. Note: the y-axes of all the distributions presented in this thesis represent probability density.....75
Figure 3.1: A curve which shows the decay of the deviation from the mean of the result under 100% population 80
Figure 3.2: The statistical map of the standardization process.....83
Figure 3.3: The energy consumption for 1000 km and 7000 km NG transport processes in the form of MJ per MJ of CGH2 fuel throughput.....85
Figure 3.4: The fit results panel showing a comparison of the fitted distributions for the GHG emissions of the ST-CGH2-NG-Central stage. Note: the shape of the distribution fit may look like a numerical artefact. This may clearly show an effect on the shape of the simulation output as in Figure 5.20. Nevertheless, the outcomes of main interest from the distribution fitting are statistics such as the mean and standard deviation.....92
Figure 3.5: An example of a case where we need to truncate the fitted distribution: The distribution function for the GHG emissions of sugarbeet supply.....93
Figure 3.6: The @Risk Define Distribution tool where distribution functions are defined by arguments 94
Figure 3.7: Summarizing a scatter diagram.....97
Figure 3.8: A scatter plot of the GHG emissions for the Feedstock Production (SP) and Feedstock Transport (ST) stages of the conventional gasoline from crude oil chain from Appendix L.....98
Figure 3.9: The Define Correlations window where the correlations between the input distributions are defined.....99
Figure 3.10: A snap shot from the WtT worksheet showing an example of an inconsistent matrix that was adjusted by @Risk 100
Figure 3.11: A snap shot showing the equation of a WtT model input cell 100
Figure 3.12: The relation between assumptions from variables of different models 101
Figure 3.13: A representation of a cumulative probability curve.....106
Figure 3.14: An illustration of the sampling of 5 random samples from the ST-CG-Crude-Oil-EM distribution by the Monte Carlo sampling method.....108
Figure 3.15: An illustration of the sampling of 5 random samples from the ST-CG-Crude-Oil-EM distribution by the Latin Hypercube sampling method.....109
Figure 3.16: A representation of the effect of Latin Hypercube sampling on the distribution of the sample mean.....110
Figure 3.17: A complete representation of output uncertainty. The y-axes of all the distributions presented in this thesis represent probability density.....112
Figure 3.18: A scatter plot reflecting the correlation between the output result and the NG production process of the CNG Well-to-Tank chain 113

Figure 3.19: A “tornado” type chart with the longer bars at the top representing the most significant stages of the chain under study. See for nomenclature to read the abbreviations. 114
Figure 4.1: The energy consumption and GHG emissions assumptions of the crude oil production process. Note: The y-axes of all the distributions presented in this thesis represent probability density. Distribution figures of larger scale can be obtained from Appendix L after using the “swap in functions” command of @Risk software which is fully integrated into the model. 122
Figure 4.2: The energy consumption and GHG emissions assumptions of the natural gas production process 123
Figure 4.3: The assumptions of energy consumption and GHG emissions of the coal production process 125
Figure 4.4: The chart of land use of different types of biomass feedstock for the production of bioethanol 128
Figure 4.5: The energy consumption and GHG emissions assumptions of the sugarcane supply process 130
Figure 4.6: The energy consumption and GHG emissions assumptions of the sugarbeet supply process 136
Figure 4.7: The energy consumption and GHG emissions assumptions of the short-rotation forestry supply process 137
Figure 4.8: The energy consumption and GHG emissions assumptions of the residual ligno-cellulosic biomass supply process 139
Figure 4.9: The energy consumption and GHG emissions assumptions of the wood-biomass supply process 141
Figure 4.10: The energy consumption and GHG emissions assumptions of the renewable electricity production process 143
Figure 4.11: The energy consumption and GHG emissions assumptions of the uranium supply process 146
Figure 4.12: The energy consumption and GHG emissions assumptions of conventional gasoline (CG) production in refinery 149
Figure 4.13: The energy consumption and GHG emissions assumptions of central SMR 151
Figure 4.14: The energy consumption and GHG emissions assumptions of onsite SMR 153
Figure 4.15: The energy consumption and GHG emissions assumptions of NG power plant 154
Figure 4.16: The energy consumption and GHG emissions assumptions of central electrolysis 155
Figure 4.17: The energy consumption and GHG emissions assumptions of onsite electrolysis 156
Figure 4.18: The energy consumption and GHG emissions assumptions associated with the production of gaseous hydrogen from wood chips 162
Figure 4.19: The energy consumption and GHG emissions assumptions of coal-fired power plant 164
Figure 4.20: The energy consumption and GHG emissions assumptions of nuclear power plant 165

Figure 4.21: The energy consumption and GHG emissions assumptions of electrolysis by nuclear electricity 167
Figure 4.22: The energy consumption and GHG emissions assumptions of the CG ICE vehicle operation 172
Figure 5.1: WtW energy consumption of NG-based chains together with that of two crude oil based chains including the reference chain. 181
Figure 5.2: The energy change distributions relative to the reference chain for various NG-based options. The emerging hybrid gasoline vehicle option is also included. 183
Figure 5.3: The WtW GHG emissions for NG-based chains. Two crude oil based chains including the reference chain are also included. 185
Figure 5.4: The GHG emissions change distributions relative to the reference chain for various NG-based options. The emerging hybrid gasoline vehicle option is also included. 186
Figure 5.5: The WtW energy consumption for various chains fuelled by renewable generated electricity together with the reference chain 187
Figure 5.6: The energy consumption distributions of various renewables-based options 188
Figure 5.7: The WtW GHG emissions of non-biomass renewables based chains 190
Figure 5.8: The GHG emissions change distributions for selected renewables-based options 190
Figure 5.9: The WtW energy consumption for nuclear-based chains 191
Figure 5.10: The energy change distributions for nuclear-based chains relative to the reference chain 192
Figure 5.11: The WtW GHG emissions for nuclear-based chains 192
Figure 5.12: The GHG emissions change distributions for nuclear-based options 193
Figure 5.13: The WtW energy consumption for coal-based chains together with the reference chain 193
Figure 5.14: The energy change distribution for the coal-based electricity option relative to the reference chain 194
Figure 5.15: The WtW GHG emissions for coal-based chains 195
Figure 5.16: The GHG emissions change distributions for coal-based options 195
Figure 5.17: The land use of different types of biomass feedstock for bioethanol production per (i) 1 U.S gallon of ethanol in vehicle tank, and (ii) 100 km 196
Figure 5.18: The complete cycle of biofuels production 197
Figure 5.19: The WtW energy consumption of biomass-based chains 199
Figure 5.20: The energy consumption distributions of selected cellulosic biomass options 200
Figure 5.21: The energy consumption distributions of sugar biomass chains 200
Figure 5.22: The WtW GHG emissions of biomass-based chains 202
Figure 5.23: The GHG emissions change distributions of selected cellulosic biomass options 203
Figure 5.24: The GHG emissions change distributions of selected sugar biomass options 204
Figure 6.1: Energy consumption in MJ/MJ_W for relevant WtW power and transport chains 217
Figure 6.2: GHG emissions in gCO_2eq/MJ_W for relevant power and transport chains 218
Figure 6.3: The changes of GHG emissions from the use of alternatives under different scenarios 220
Figure 7.1: The current study approach 226

Figure 7.2: The forecast and historical data of UK passenger cars traffic 229
Figure 7.3: The area chart of scenario 1 showing the contribution of different deliverables (i) at any point in the time series and (ii) over any time period within 2010-2080 231
Figure 7.4: The area chart of scenario 2 showing the contribution of different deliverables (i) at any point in the time series and (ii) over any time period within 2010-2080 235
Figure 7.5: The area chart of scenario 3 showing the contribution of different deliverables (i) at any point in the time series and (ii) over any time period within 2010-2080 237
Figure 7.6: The area chart of scenario 4 showing the contribution of different deliverables (i) at any point in the time series and (ii) over any time period within 2010-2080 238
Figure 7.7: The area chart of scenario 5 showing the contribution of different deliverables (i) at any point in the time series and (ii) over any time period within 2010-2080 239
Figure 7.8: The area chart of scenario 6 showing the contribution of different deliverables (i) at any point in the time series and (ii) over any time period within 2010-2080 240
Figure 7.9: The scale of effect on the environment in terms of GHG emissions from the progressive implementation of different framework scenarios.....241
Figure 7.10: The scale of effect on the depletion of energy resources from the progressive implementation of different framework scenarios 243

List of Tables

Table 1.1: An illustration of the effect of variable modelling elements on the WtW energy consumption and GHG emissions for three selected options....7
Table 1.2: Comparison between the type of results currently available and those provided by the STM....11
Table 2.1: A comparison of the life cycle for PEMFC and ICE vehicles (source: Hussain et al., 2007)....30
Table 2.2: The NG-based options under assessment....38
Table 2.3: The biomass-based options under assessment....38
Table 2.4: The non-biomass renewables based options under assessment....39
Table 2.5: The nuclear-based options under assessment....39
Table 2.6: The coal-based options under assessment....39
Table 2.7: The crude oil based options under assessment....39
Table 2.8: The data for the modelling of a hydrogen WtT system....45
Table 2.9: The different measures of energy consumption for the models presented in Figure 2.12 50
Table 2.10: The description of the data required to model the assumed sub-system and construct data in the desired form....55
Table 2.11: The GWPs of Greenhouse Gases. Source: (IPCC, 1996)....59
Table 3.1: The results of the simulation output with varying percentage of the full population as an input to the model....79
Table 3.2: A section of the datasets generated for the WtT-CGH2-NG-Central chain from Appendix L....89
Table 3.3: An example of a data filter....90
Table 3.4: A key for Eq. 3.16 and Eq. 3.17 also showing the two types of results generated in the current project 102
Table 3.5: Random samples of x1 and x2 with rank scores according to the positioning of the random numbers within the 0-1 range....111
Table 4.1: The land use of different types of biomass feedstock for the production of bioethanol 128
Table 4.2: The direct land use change emissions of farming/collecting the biomass feedstock under consideration in the STM from GREET v.1.8c (ANL, 2009)....134
Table 4.3: Renewable resources potential (Goldemberg, 2000) 142
Table 4.4: Energy consumption and GHG emissions associated with the manufacturing of renewable and non-renewable feedstock production processes. Source: GEMIS v.4.5 (Öko-Institut, 2008) 144
Table 4.5: The energy consumption and GHG emissions of transport of different types of feedstock....147
Table 4.6: The energy consumption and GHG emissions associated with the fermentation of different types of biomass feedstock....157
Table 4.7: The energy consumption and GHG emissions associated with the distribution of different types of fuel 168

Table 4.8: The major factors that underpin the variability of the STM output 174
Table 5.1: Capital cost of electricity storage (Converse, 2006) 189
Table 7.1: Framework deliverables 227

Glossary of Terms[2]:

Well-to-Wheel chain	A chain that describes the energy system under study and extends from the source of the primary resource (e.g. Crude oil) to the end use powertrain (e.g. H_2 fuel cell vehicle).
Well-to-Tank chain	A chain that describes the fuel production and distribution. Also known as the fuel chain and extends from the source of the primary feedstock to the tank of the fuel (e.g. vehicle tank).
Tank-to-Wheel stage	The stage of fuel conversion into work done through a powertrain.
Process	One unit of an energy system (e.g. refinery). Sometimes has an expanded meaning and refers to a stage consisting of two processes.
Stage	A subset of a chain consisting of one or more processes (e.g. NG production which is composed of the NG recovery and the NG processing processes).
System	A group of interlinked processes which deliver a product of energy or work done. Commonly used to refer to a complete chain (WtW chain).
Chain	A group of interlinked stages which deliver a product of energy or work done.
Change distribution	The distribution of difference between the alternative chain and the conventional chain in terms of GHG emissions or energy consumption.
Conversion efficiency	The efficiency of a process without the account of energy credit associated with co-products generation or energy debt associated with process fuel supply. Named after the GREET model. Commonly referred to as "efficiency". However, the word efficiency may also refer to the life cycle efficiency or the feedstock conversion efficiency depending on the boundary of the calculation which is defined in the context of the discussion.
Downstream	Towards the end of the chain.
Feed loss	The feedstock that is lost in the conversion process (e.g. the amount of NG other than the fuel that is wasted in the SMR).
Feedstock loss	The energy losses due to unusual leakages in the process such as spillage and boil-off.
Model	A graphical and mathematical representation of a pathway under study. Also used to generally refer to a reference model (e.g. GEMIS).
Modelling element	An element which describes an assumption, choice or parameter of a model/system assumption (e.g. land use change, geographic distance, SMR plant design).
Opportunity zone	The negative (-) proportion of the change distribution where the alternative chain consumes less energy or emits less GHG emissions relative to the conventional chain.
Pathway	One route of a chain or option under study (e.g. NG from North Sea

[2] Six key terms listed in order of explanation; then rest are alphabetical.

	transported by HP pipeline over a specific distance to a central reformer followed by H2 distribution by pipeline to a fuel cell vehicle).
Process fuel	The fuel used in the process (e.g. electricity, NG, mechanical energy).
Risk zone	The positive (+) proportion of the change distribution where the alternative chain consumes more energy or emits more GHG emissions relative to the conventional chain.
Sample element	A data element of the sample; the number associated with a system assumption.
Sampled population	The part of the target population under consideration by the STM.
Sample space	The multidimensional space which represents all the output possibilities in the particular universe under consideration by the STM.
Scenario	A sequence of events which refers to either (i) a synergistic link between two sectors or (ii) a future outlook.
Sensitivity	The meaning of this term depends on the purpose of the analysis. Sensitivity can refer to the impact of a variable on the result. Also sensitivity can refer to the contribution of a variable to the uncertainty of the result.
System assumption	A model of the process or processes which describe one stage of the STM. Also referred to as an "input assumption".
Target population	The totality of the system assumptions that are thought in literature for one stage of the STM. Also refers to the unlimited universe of output possibilities.
Upstream	Towards the beginning of the chain.
Upstream process	A process in the chain of the process fuel supply.

List of Nomenclature

ANL	Argonne National Laboratory
AOX	Adsorbable Organic Halides
AP	Associated Press
ASPO	The Association for the Study of Peak Oil
BEV	Battery Electric Vehicle (all-electric)
BOD	Biological Oxygen Demand
Btu	British thermal unit
CCS	Carbon Capture & Sequestration
CCGT	Combined Cycle Gas Turbine
CEFs	CO2 Equivalency Factors
CG	Conventional gasoline
CGH2	Compressed Gaseous Hydrogen
CNG	Compressed Natural Gas
COD	Chemical Oxygen Demand
CVTF	Cleaner Vehicles Task Force
DE	Germany
DECC	Department of Energy & Climate Change
DETR	Department of Environment, Transport and the Regions
DfT	Department for Transport
DOE	Department of Energy
DJ	Dow Jones Newswires
dLUC	Direct land use change
DTI	Department of Trade and Industry
EC	Energy consumption
EIA	Energy Information Administration
EM	GHG emissions
EPA	Environmental Protection Agency
EREC	European Renewable Energy Council
EST	Energy Savings Trust
EtOH	Ethanol
EUROPEN	The European Organization for Packaging and the Environment
FC HEV	Fuel Cell Hybrid Electric Vehicle
FCV	Fuel Cell Vehicle
FD	Fuel Distribution
FP	Fuel Processing
FR	France
FT	Feedstock Transport
gCO_2eq	Grams of Carbon Dioxide Equivalent
GEMIS	Global Emission Model for Integrated Systems
GH2	Gaseous Hydrogen
GHG	Greenhouse Gas
GM	General Motors Corporation
GM-LBST	General Motors and Ludwig Bölkow Systemtechnik
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GT	Gas Turbine

Gt	Giga tonnes
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
HFCs	Hydro Fluoro Carbons
HGV	Heavy Goods Vehicle
HHV	High Heating Value
HP	High Pressure
HTGR	High Temperature Gas-cooled Reactor
ICEV	Internal Combustion Engine Vehicle
IC HEV	Internal Combustion Hybrid Electric Vehicle
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
iLUC	Indirect Land Use Change
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
iRUC	Indirect Resource Use Change
ISO	International Organization for Standardization
ITPOES	Industry Task Force on Peak Oil and Energy Security
JEC	Joint Research Council, EUCAR and CONCAWE
$kgCO_2eq$	Kilograms of carbon dioxide equivalent
kWh	Kilowatt-hour
LBST	Ludwig Bölkow Systemtechnik
LCA	Life Cycle Assessment
LDV	Light Duty Vehicle
LEM	Lifecycle Emissions Model
LH2	Liquid Hydrogen
LHS	Latin Hypercube Sampling
LHV	Low Heating Value
LNG	Liquid Natural Gas
LP	Low Pressure
LPG	Liquid Petroleum Gas
LUC	Land Use Change
LWR	Light Water Reactor
MIT	Massachusetts Institute of Science and Technology
MJ_{fuel}	Mega Joules of fuel output
MJ_W	Mega Joules of work done (e.g. driving)
MMBtu	Million British thermal units
MPG	Miles per gallon of petrol
$MtCO_2eq$	Million tonnes of carbon dioxide equivalent
Mtoe	Million tonnes of oil equivalent
NA	North America
N/A	Not applicable
NMOGs	Non-Methane Organic Gases
NMVOC	Non-Methane Volatile Organic Compounds
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries

PDF	Probability Density Function
PEMFCV	Polymer Electrolyte Membrane Fuel Cell Vehicle
PFCs	Perfluorocompounds
PM10	Particulate matter of less than 10 micrometres
PM2.5	Particulate matter of less than 2.5 micrometres
PSA	Pressure Swing Adsorption
ROM	Run-of-Mine
ROR	Run-of-River
RSD	Relative Standard Deviation (coefficient of variation)
RU	Russia
SCGT	Single Cycle Gas Turbine
SF6	Sulfur hexafluoride
SI	Shell International
SMR	Steam Methane Reforming
SRF	Short-Rotation Forestry
ST	Steam Turbine
STM	Standardization Transport Model
TEC	Total energy consumption
TEI	Total energy input
TEMIS	Total Emission Model for Integrated Systems
TEU	Total energy use
TtW	Tank-to-Wheel
UN	United Nations
UNGA	United Nations General Assembly
VOCs	Volatile Organic Compounds
WtT	Well-to-Tank
WtW	Well-to-Wheel
ZA	South Africa
0LUC	No account of land use change

Key for abbreviations used to indicate STM variables:

Stage-Fuel-Resource-Conversion process design-Vehicle-Dimension

Examples:

SP-CGH2-NG-Decentral-EC	Stage: Feedstock production Fuel: Compressed gaseous hydrogen Resource: Natural gas SMR process design: decentral (onsite) Vehicle: not applicable in Well-to-Tank chains Dimension: Energy consumption
WtW-CGH2-NG-Central-w/CCS-FCV-EM	Stage: Well-to-Wheel (complete chain) Fuel: Compressed gaseous hydrogen Resource: Natural gas SMR process design: central with CCS technology Vehicle: Fuel cell vehicle Dimension: GHG emissions
WtT-CG-Crude-Oil-ICEV-EC	Stage: Well-to-Tank (fuel chain) Fuel: Conventional gasoline Resource: Crude oil Refinery process design: no special design Vehicle: Internal combustion engine vehicle Dimension: Energy consumption

1 Introduction and Problem Context

1.1 Research background

The general motivations of research in the context of sustainable energy are nicely laid out by David MacKay, a Professor in the Department of Physics at the University of Cambridge and a Fellow of the Royal Society, in his recent book entitled "Sustainable Energy – without the hot air" (Mackay, 2009b, p.5). He identifies three drivers: (i) fossil fuels are a finite source and indeed a valuable resource useful for the manufacture of plastics and other chemicals and that we should save them for these better uses, (ii) the security of energy supply is of much interest to policy makers, and (iii) the biggest contributor to climate change is the increase in the greenhouse effect produced by carbon dioxide (CO_2) which mainly comes from the burning of fossil fuels.

All of the three concerns as defined by Mackay stem from one problem and that is the energy problem. The main reason fossil fuels are burned is for energy and therefore the climate problem is mostly an energy problem. Also the reduction of fossil fuels consumption is the key to increasing energy security at a local level, by decreasing dependency on foreign resources, as well as at a global level by contributing to the avoidance of a global energy crisis which spares no nation. The 1974 energy crisis may be seen as only a sign of warning for what will occur after worldwide oil and gas production reaches its peak. Although the date is very uncertain the World is approaching the point at which increases in oil and gas production are impossible. If production declines and the demand continues to incline there will be an increasing "energy gap" with severity of consequences (Bently, 2002). Indeed based on the results of the last conference held by The Association for the Study of Peak Oil (ASPO), a global network for the study of the date and impact of the peak and decline of the World's production of oil and gas, in October 2009 in Denver, USA, Chris Nelder says: *"We now know that conventional crude did in fact hit its peak-plateau in 2005, having remained around the 74 Mb/d (Million barrels per day) level ever since (ITPOES, 2010)."* Probably the consequences of such a peak are not yet felt because of the cash crunch in 2008 which moved the World's economies from vigorous growth to deep economic recession.

Thus, the progressive elimination of fossil fuels from the energy markets is the key solution to all concerns. However, it is essential to examine energy alternatives very carefully. For instance,

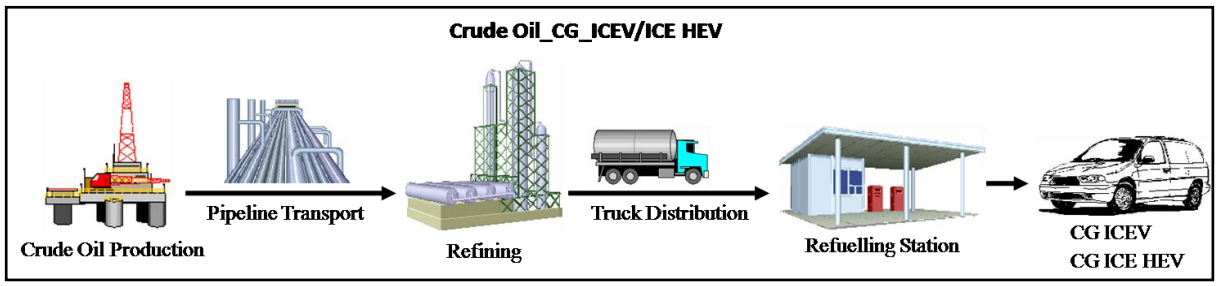
there is a growing debate on the CO_2 reductions from biofuels which is a well thought alternative to fossil fuels.

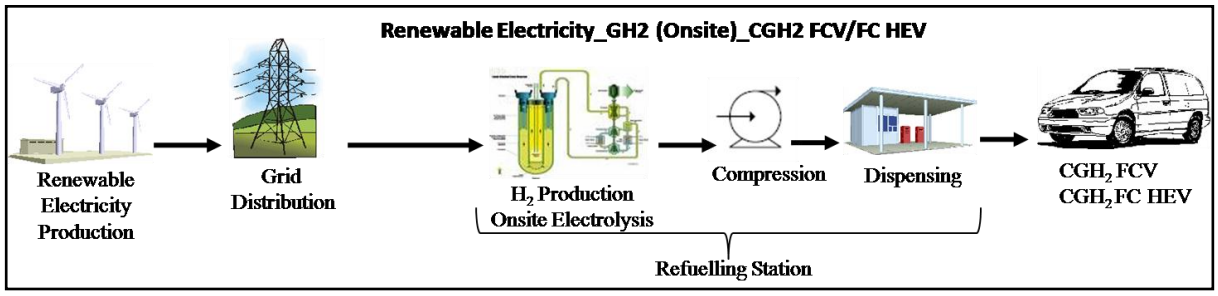
The particularly driver of this project is transport which is a major user of fossil fuels. For instance, in the UK transport made up 37% of the final energy consumption in 2009 which is estimated at 152.7 Mtoe (Million tonnes of oil equivalent); out of which 95% is petroleum, 1% coal and 1% NG (DECC, 2010b, p.14 & 21). The achievement of the targets set by the Kyoto Protocol and elsewhere means that the national governments must reduce CO_2 emissions in all sectors including the transport sector which is at the top of the list for fossil fuel consumption and CO_2 production. More specifically, the scope of this project is limited to the development of passenger cars transport which indeed is responsible for the largest proportion of Greenhouse Gas (GHG) emissions in transport. For instance, in the UK passenger cars transport made up 55% of the total transport GHG emissions in 2008 which was estimated at 131.9 $MtCO_2eq$ (Million tonnes of CO_2 equivalent) by the UK Department of Energy and Climate Change. These emissions statistics are as revised on 14 April 2010 (DECC, 2010a, Table 3).

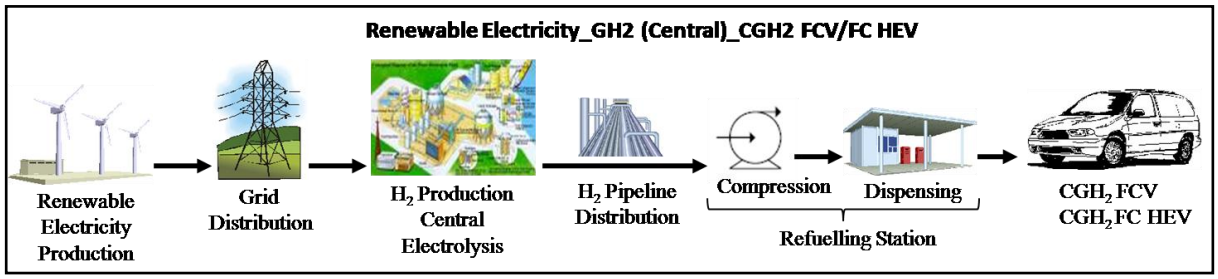
1.2 Thesis contribution in the context of energy research

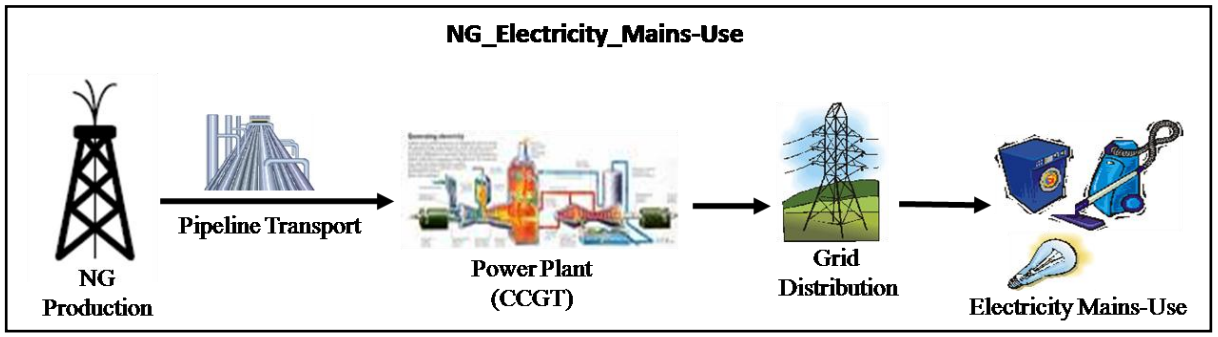
1.2.1 The Standardization Transport Model (STM)

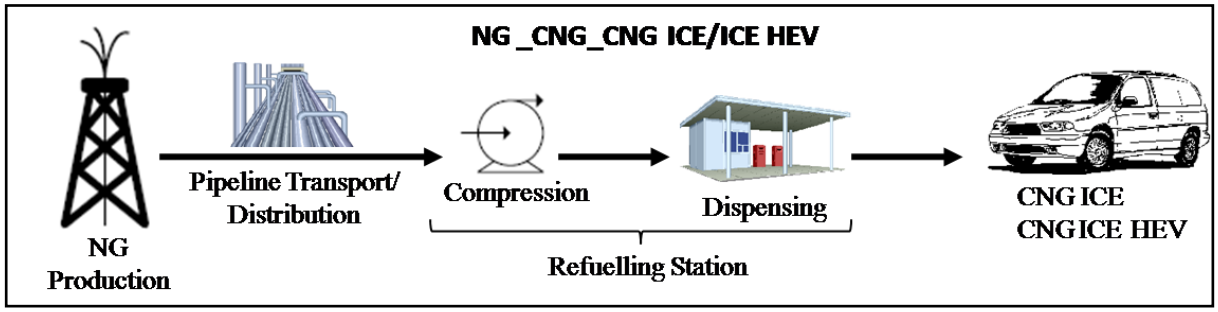
The Life Cycle Analysis (LCA) approach is a powerful tool for looking at the future; according to Hickman and Banister (2007) this is particularly important when dealing with policies relating to sustainable transport because many interventions require considerable time to be effective. The Well-to-Wheel (WtW) model is a graphical and mathematical description of a fuel life cycle (cradle-to-grave or source-to-use system) which is used to measure and compare the overall impacts, such as GHG emissions and energy consumption, of potential alternatives, most commonly, in the transport sector. See Figure 1.1 below for a diagrammatic representation of different WtW chains. The WtW chain is a combination of Well-to-Tank (WtT) and Tank-to-Wheel (TtW) components. (The TtW stage is where the powertrain, e.g. vehicle, is used.) Due to concerns regarding Global Warming and energy security there has been increasing interest in the WtW assessment of automotive fuels. Such analyses are increasingly required to assess the global implications of prospective transport options for medium to long term futures. (More details on the WtW model are given in Chapter 2.)


Crude Oil_CG_ICEV/ICE HEV
Crude Oil Production
Pipeline Transport
Refining
Truck Distribution
Refuelling Station
CG ICEV
CG ICE HEV


Renewable Electricity_GH2 (Onsite)_CGH2 FCV/FC HEV
Renewable Electricity Production
Grid Distribution
H2 Production Onsite Electrolysis
Compression
Dispensing
CGH2 FCV
CGH2 FC HEV
Refuelling Station


Renewable Electricity_GH2 (Central)_CGH2 FCV/FC HEV
Renewable Electricity Production
Grid Distribution
H2 Production Central Electrolysis
H2 Pipeline Distribution
Compression
Dispensing
Refuelling Station
CGH2 FCV
CGH2 FC HEV


NG_Electricity_Mains-Use
NG Production
Pipeline Transport
Power Plant (CCGT)
Grid Distribution
Electricity Mains-Use


NG _CNG_CNG ICE/ICE HEV
NG Production
Pipeline Transport/ Distribution
Compression
Dispensing
Refuelling Station
CNG ICE
CNG ICE HEV

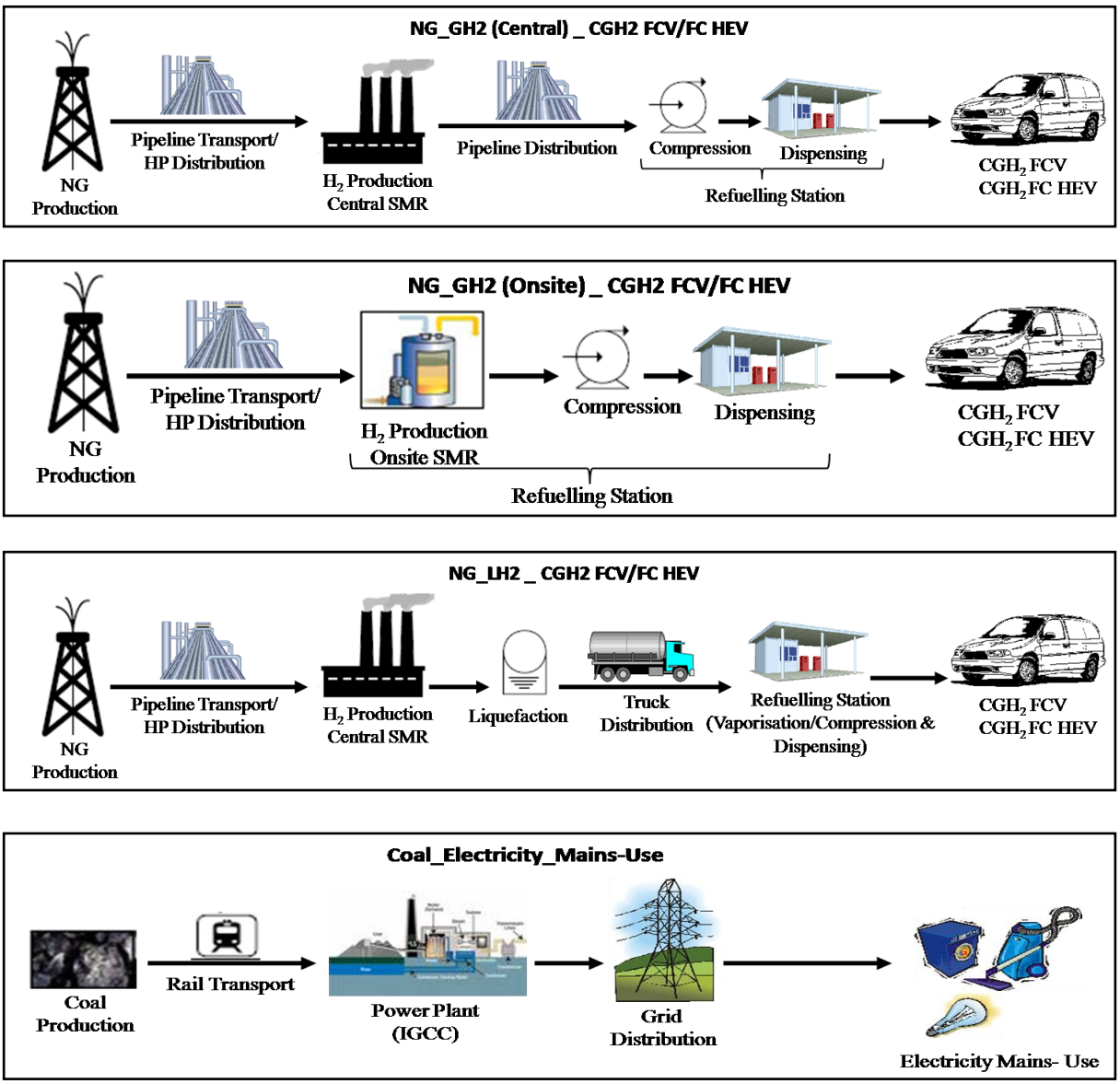


Figure 1.1: A diagrammatic representation of different WtW chains (built for representative purposes from the pathways under consideration in the STM which are introduced in Chapter 2)

However, while Mankind is urged to mitigate climate change and energy scarcity, it is puzzling to notice that most of the transport WtW studies today do not perform policy analysis but rather present the differences between some specific existing and some selected future transport options in terms of defined metrics (e.g. GHG emissions). The question herein is whether it is feasible to integrate transport WtW studies into strategic energy planning and if so, how?

The application of the WtW analysis in strategic planning is limited by the *quality* of the results. However, before discussing the adequacy of the results of existing transport WtW models for policy making it is worth asking a question: What does "quality" herein refers to? In this respect

reference is made to the British Standard Institution which defines quality under BS 4778: *"The totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs"* (Doherty, 1994, p.7). The main idea behind this definition is that quality relates to the necessity of satisfying certain needs, or what could be defined as the 'fitness for purpose'. The process of strategic energy planning involves making important decisions and therefore the information used should necessarily fulfil the requisite of being reliable. Thus the quality of a WtW result in this context is summarized by one word and that is "reliability".

A model is said to be *deterministic* when the input parameters are specific; and *stochastic* when at least one of the input parameters is probabilistic. The output of the individual WtW models today is either (i) determined and provides no insight whatsoever into the uncertainty of the result, or (ii) pseudo random where the primary input parameters are stochastic and represent what is commonly referred to as subjective uncertainty which is mainly judgmental but may involve an expert review process. The latter type of output may be successful in conveying some uncertainty to decision makers, but it falls short of addressing the actual uncertainty of the output.

Unfortunately the uncertainty presented by the classic types of WtW results is constrained to one database and a particular set of input assumptions and choices. The truth is that far from delivering the reliability required for strategic energy planning the associated model does not measure the uncertainty across databases, across assumptions and across choices but instead maintains individualism and determinism in the analysis. In contrast the Standardization Transport Model (STM) which is developed in this project represents a new initiative and is concerned inter alia with the variability of the input parameters across different databases as well as the variability of the modelling choices and assumptions across different models. The current scope of the STM is confined to passenger cars transport.

A group of factors that describe the WtW model have been identified and in the rest of this study are referred to as the "modelling elements". These include but are not limited to the model database, system boundary, type and design of process chosen, modelling assumptions, methodological choices, geographic distances and time frame. An example of a different type of process for the same area would, in the area of electricity from coal, be the choice between IGCC (Integrated Gasification Combined Cycle) and steam turbines. Regarding process design for a

given choice of process there are clearly different options that can be considered such as the steam methane reforming (SMR) with electricity co-production or steam co-production. Various modelling assumptions have to be made from simple matters such as the choice of system distribution pressure to decisions on the system boundary. An example the latter is whether to include the GHG emissions from land use change (LUC) and if so, as direct or indirect LUC. Other less important assumptions include the type of electricity being substituted for when calculating the carbon credit from co-producing electricity and distributing to a user site (e.g. is it coal based electricity or NG based electricity?). Under the heading of methodological choices we include the modelling structure, the allocation method in the case of co-products and for heating values whether it is HHV or LHV.

Whilst in the past decade there have been developments in WtW modelling, including the integration of stochastic applications which propagates some uncertainty inherent in the lifecycle inventory through to the model results, there remains the problem of significant discrepancies in the WtW results. This illustrates what was emphasized earlier about the individual and determined nature of pseudo random results. So currently used are methods far from delivering the reliability required in the context of strategy planning. The differences that are due to the variability of modelling elements can be seen as an obstacle that must be overcome in order to produce a robust energy strategy. However here it is asserted that this problem is a blessing in disguise as these differences are a measure of the uncertainty generated by the expert systems. Thus the incorporation of the richness of the information embedded in the major comprehensive models into one STM allows one, with the appropriate use of sensitivity analysis, to probe the major disagreements in assumptions, choices and parameters across different models.

That there are differences to consider will now be illustrated with respect to sugar cane ethanol fuelling an internal combustion engine vehicle (ICEV and two other options for passenger transport fuels in Table 1.1 below. (Abbreviations used in Table 1.1 are defined immediately after it.) The ranges for both WtW energy consumption and GHG emissions are shown to be around a factor of two.

Table 1.1: An illustration of the effect of variable modelling elements on the WtW energy consumption and GHG emissions for three selected options

Database	WtW Energy consumption	WtW GHG emissions	Description
	(MJ/km)	**(gCO_2eq/km)**	
Sugarcane ethanol in Internal Combustion Engine Vehicle (ICEV)			
GEMIS (1)	12.42	98.86	0LUC; fermentation, efficiency 20.7%, yield: 86 l/t; design: 89% ethanol, 11% electricity; allocation by credit; transport of EtOH, ship-ocean 9000 km; truck mix distribution, 100 km; RY 2005
GEMIS (2)	12.42	98.55	dLUC (arable), fermentation, efficiency 20.7%, yield: 86 l/t; design 89% ethanol, 11% electricity; allocation by credit; transport of EtOH, ship-ocean 9000 km; truck mix distribution, 100 km; RY 2005
GEMIS (3)	12.42	267.32	iLUC (arable), fermentation, efficiency 20.7%, yield: 86 l/t; design 89% ethanol, 11% electricity; allocation by credit; transport of EtOH, ship-ocean 9000 km; truck mix distribution, 100 km; RY 2005
GREET (1)	6.81	138.12	dLUC = 0; fermentation, w/o co-product, yield: 90.9 l/t (50% H2O); ethanol T&D; RY 2010
JEC (1)	5.34	26.67	0LUC; fermentation, w/heat export (0.115 $MJ/MJ_{ethanol}$), yield: 98.1 l/t (72.5% H2O); allocation by credit, replaced system: light heating oil fuelled boiler; ethanol T&D; RY 2010
GHGenius (1)	6.42	98.14	dLUC; fermentation; ethanol T&D; RY 2010
Range	***5.34-12.42***	***26.67-267.32***	
Nuclear electricity in Battery Electric Vehicle (BEV)			
GEMIS (1)	2.64	7.69	Uranium enrichment 30% diffusion, 70% centrifuge; PWR, efficiency 33%; system boundary: include process manufacturing; RY 2000
JEC (1)	3.03	3.54	Significant uranium losses in UF6 production; uranium enrichment by 100% diffusion; PWR type of reactor, plant efficiency of 33%; time frame of 2010-2020
GREET (1)	1.21	4.80	Uranium enrichment 25% diffusion, 75% centrifuge; LWR, efficiency 100% (uranium fuel accounted as active material, not energy resource); RY 2010
GREET (2)	1.21	4.68	No uranium losses in UF6 production; uranium enrichment by 25% diffusion, 75% centrifuge; HTGR type of reactor, plant efficiency of100% (uranium fuel accounted as active auxiliary material); time frame of 2010
Range	***1.21-3.03***	***3.54-7.69***	
Compressed Natural Gas (CNG) in ICEV			
GEMIS (1)	2.83	179.34	NO NG; pipeline, HP 1950 km, LP 10 km; compression; RY 2010
GEMIS (2)	3.33	213.77	RU NG; pipeline, HP 5000 km, HP 250 km distribution; LP 10 km; compression; RY 2010
GEMIS (3)	3.01	192.75	North African NG; LNG transfer, ship-ocean 3000 km, HP 250 km after vaporization; LP 10 km; compression; RY 2010
JEC (1)	2.08	123.87	EU-mix NG; pipeline, 1000 km; compression; RY 2010
JEC (2)	2.09	134.72	South Western Asia NG; pipeline, 4000 km; compression; RY 2010
JEC (3)	2.45	145.37	LNG transfer, ship-ocean 11186 km; vaporization, HP 500 km, LP 10 km distribution; RY 2010-2020
JEC (4)	2.37	146.68	LNG transfer, ship-ocean 11186 km; trucker distribution; vaporization/compression; RY 2010-2020
GREET (1)	3.94	248.92	NA NG; pipeline 1207 km; compression 0.345 to 25.60 MPa ; RY 2010
GM-LBST (1)	3.06	182.53	RU NG; pipeline 7000 km + distribution; compression inlet pressure 0.1 MPa; RY 2010
GM-LBST (2)	3.27	197.06	RU NG; pipeline 7000 km + distribution; compression inlet pressure 4.0 MPa; RY 2010
GM-LBST (3)	2.77	167.77	LNG transfer, ship-ocean; trucker distribution; vaporization/compression; RY 2010
Range	***2.08-3.94***	***123.87-248.92***	

Abbreviations: 0LUC: no account of C emissions from land use change; dLUC: include C emissions from direct land use change but without indirect land use change; iLUC: include C emissions from direct and indirect land use change; RY: Reference year of technology; PWR: Pressurized Water Reactor; HTGR: High Temperature Gas-cooled Reactor; LWR: Light Water Reactor; NO: Norwegian; RU: Russian; NA: North American; LNG: liquid natural gas; HP: high pressure line; LP: low pressure line.

Assumptions: (1) The energy consumption and GHG emissions associated with the vehicles operation is assumed for the GEMIS WtW calculations as average of measures from MIT, GREET, JEC, GM-LBST and LEM models; (2) The BEV energy consumption is assumed for the JEC WtW calculations as average of measures from MIT, GREET and LEM models. Note: The information in the description column reflect some but not all of the sources of variability. Sources: (JRC *et al.*, 2008c, 2008b; Weiss *et al.*, 2000; GM *et al.*, 2002a; $(S\&T)^2$ Consultants Inc., 2009; Öko-Institut, 2008; ANL, 2009; Delucchi, 2003).

Given the variability it is unsurprising that there is disagreement regarding major subjects such as the viability of the hydrogen economy and the carbon footprint of biofuels. Such disagreements are not as opinionated as some may suppose as in part they arise from the variability of modelling elements across the different models that were used to measure the impacts of these options. To reflect the strong disagreement in broad principle over the future of transport fuels we quote some opposing point of views:

"...the answer to the question: "Does a Hydrogen Economy make Sense?" is an unconditional "NEVER". A global hydrogen economy has no past, present or future!" Ulf Bossel, Head of European Fuel Cell Forum, Switzerland (Bossel, 2005)

"Hydrogen is a very attractive alternative fuel" Prof. Peter Edwards, University of Oxford, Coordinator of UK Sustainable Hydrogen Energy Consortium (Edwards *et al.*, 2008)

"A switch to a fuel cell operating with on-board compressed gaseous hydrogen derived from EU-mix NG reduces GHG emissions by almost 38%" GM European WtW study, 2002 (GM *et al.*, 2002b)

"Hydrogen-powered vehicles, for one, are a disaster" David MacKay, The Sunday Times, 2009 (Mackay, 2009a)

"Use of U.S. croplands for biofuels increases GHG through emissions from land use change" T. Searchinger, University of Princeton, Science, 2008 (Searchinger *et al.*, 2008)

"On the basis of our own analyses, production of corn-based ethanol in the United States so far results in moderate GHG emissions reductions" Michael Wang, Argonne National Laboratory, 2008 (Wang and Haq, 2008)

"Biofuels cause four times more carbon emissions", according to a report for the European Commission, Telegraph, 2010 (Gray, 2010)

The difficulty in resolving some of these controversies is seen by the author as being due to two factors. Firstly current output is generally confined to be within the box of a particular model and

no account of different perspectives is included. Secondly current output is generally confined to a determined set of assumptions and choices and no account of changes in the modelling elements is included. Whilst it is sometimes useful to analyse why models produce differences the generation of the STM rests upon the conviction that there is a need for some synthesis as it would be irresponsible to base a strategic decision upon a single individual set of assumptions, choices and parameters.

In looking back at the history of automobiles one can see that the gasoline infrastructure has successfully served us for more than a century with the first gasoline-fuelled vehicle introduced in 1885 (Eckermann, 2001). Learning from history one should be aware that any decision made today may induce an infrastructural development that serves for many decades from now. Thus, the commissioning of projects today should be based on responsible decision making that accounts for changes in the long term future including potential changes that may not be apparent at this point in time, otherwise, the results would have dramatic consequences with the decommissioning of unwanted infrastructure and the consequential wasting of huge investments.

In methodological terms, the generation of a reliable measure that accounts for the effect of variable modelling elements and looks outside the box of one individual model requires a method that combines different WtW models without suppressing the information inherent in the variability. Currently all the WtW models, including those that integrate a stochastic application, can only model output using their own default modelling elements. In this study, a first-of-its-kind standardization model is introduced. The STM not only combines major comprehensive models in the field including those from the Institute of Applied Ecology (Öko-Institut, 2008) and the Joint Research Council, EUCAR and CONCAWE (Edwards *et al.*, 2007) in a manner that reflects the actual uncertainty in measures such as GHG emissions but, it can also be used to provide a reliable evaluation of the choices confronting decision makers in governments and the automotive industry.

1.2.2 Nature of results from the STM

The figure below presents the origin of the STM output (e.g. the GHG emissions from the production, distribution and use of conventional gasoline in an internal combustion engine vehicle). As shown the STM output can be teased out to the modelling elements that underpin

the input sample at each stage of the model. The input sample stems from the target population which is defined later in Chapter 3.

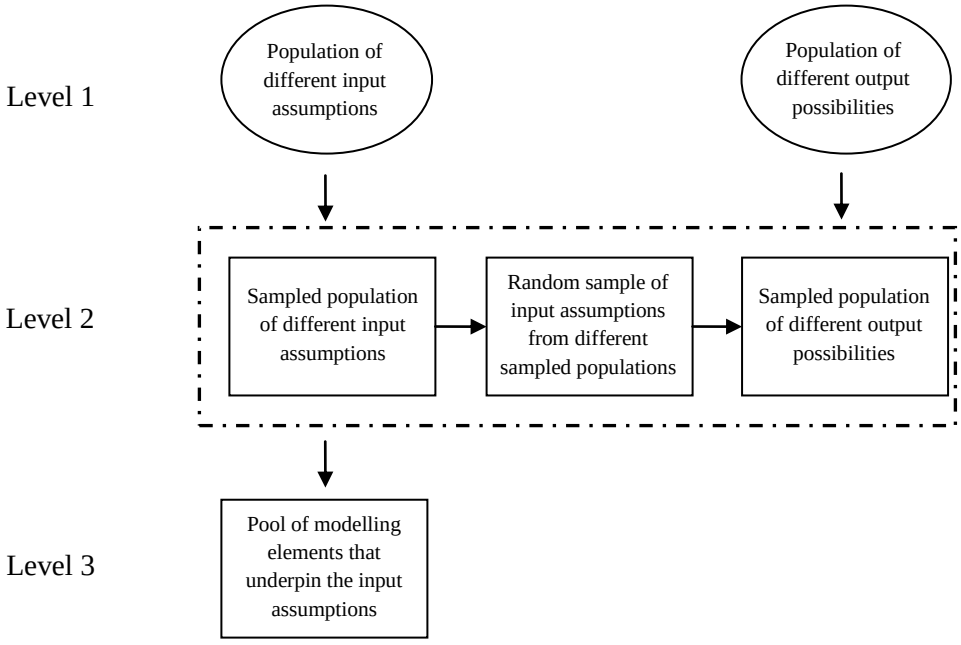


Figure 1.2: The roots of the STM output. Level 1 relates to target population. Level 2 is the sampled population used in the modelling. Level 3 is the set of modelling elements which describe the data elements of the sampled population.

The modelling elements should not be confused with the data elements of the input sample or the input assumptions, commonly referred to in the current thesis as system assumptions; in fact these are defined to describe the data elements of the input sample. The uncertainty of the STM output stems from the uncertainty of the input assumptions which is a superimposed effect of the variation in the modelling elements. Within the pool of modelling elements that underpin the input sample, a modelling element such as the plant type is not necessarily different; however by increasing the size of the pool of our consideration we increase confidence. This confidence is much larger when the pool expands to include different perspectives.

The output of the STM is an *aggregate* of the possibilities of what may occur in reality where each possibility has an equal chance of occurring in reality. The reliability of the measure refers to our confidence that what may occur in reality is under consideration. In assessing the reliability of the output measure of a model, one can ask questions such as: “Are the parameters accurate?, Are the geographic distance assumption(s) complete? Are the system type assumption(s) complete?”. Now instead of preferring one major WtW model over another, the

STM combines the modelling elements that describe the different system assumptions under consideration using the major models in the field. This increases confidence in the accuracy of parameters, the completeness of assumptions and judgement on the soundness of choices embedded in the model. Therefore the STM smoothes the standing of single individual assumptions, choices and parameters in the sense that the output reflects the richness of the assumptions embedded within existing models and none of the assumptions is standalone in the analysis. Thus any flaw in the analysis (e.g. the assumption of nuclear power plant efficiency) is allowed to go through the model but with less impact on the output. On the contrary, in classic WtW analysis flaws go through the model with full impact on the output and thus on the assessment. The effect of standardization on the reliability of the output measure can also be seen as buffering against the changes in the modelling elements across different models which as shown in Table 1.1 above can have very significant effect on the results. The effects of standardization gives a more reliable output measure that buffers against the variation in modelling elements taking into account different perspectives.

Table 1.2: Comparison between the type of results currently available and those provided by the STM

Type of results provided by classic WtW models	**Type of results provided by the STM**
Determined or "pseudo-random" measure (uncertainty under default modelling elements or no uncertainty at all)	*"Full-bodied" random measure (includes uncertainty under variable modelling elements)*
Not reliable enough within the scope of policy making (due to lack of confidence in the completeness of assumptions made and accuracy of parameters used in the model)	*Reliable enough within the scope of policy making (does not give the full weight to any particular stand alone assumptions, choices and parameters)*
Uncertainty and sensitivity analysis under variable modelling elements is NOT possible (cannot measure uncertainty from the variation in the modelling elements)	*Uncertainty and sensitivity analysis under variable modelling elements is possible (can measure uncertainty from the variation in the modelling elements)*
Confined to the inside of the box of one model	*Looks outside the box of one model (provides a birds-eye view)*

A comparison of the utility of WtW analyses and the STM is given in Table 1.2. To summarize: The standard result arises from looking outside of the box of one model and presents a reliable aggregate that smoothes the standing of single individual assumptions, choices and parameters, and buffers against changes in the modelling elements including changes with time that may not be foreseen at this stage. The STM seeks to bridge the gap between specific WtW analysis and policy making by portraying the complete picture about various options. It generates a statistically sound probabilistic measure which depicts the variability of the output from the

variability of the modelling elements across different models. In doing so it is not just another new opinion but is a robust and comprehensive model built upon the databases of pre-existing esteemed models. Having pooled the knowledge embedded in the pre-existing WtW models and generated statistically sound output, robust statements can be made. It is our contention that the STM will aid the energy debate. On the other hand, for any given chain one can probe the output of the corresponding STM and identify the major sources of disagreement. Finally, the STM output is not simply a compilation of the output results from different models; the STM is statistically valid, it allows sensitivity and uncertainty analyses and one can correlate an output portfolio of one chain with that of another in a comparative analysis.

1.2.3 The uses of the STM

This project is mainly dedicated to the development of the STM to measure the uncertainty arising from the variation in the assumptions, choices and parameters from across the major WtW models in the field. First, advantage is taken of the richness of the STM outputs to assess the sensitivity of the results and identify the major factors of disagreement within the expert systems. Here the STM presents the first comprehensive comparative evaluation of the different major WtW models. Second, the key outputs of the model are compared under the criterion of sustainability from both energy and environmental perspectives. Advantage is taken of the sensitivity analysis to estimate the correlations between the STM outputs and to setup an analytical simulation to measure the stochastic change in the GHG emissions or energy consumption relative to a reference system. Thirdly, synergies with the power sector were studied to identify which strategies delay the global reduction in GHG emissions. Last and not least, the outcomes of the comparative analyses of the STM results are aggregated into a proposed strategic framework for carbon and energy reduction in passenger cars transport. The strategic framework is placed into perspective by building a set of future scenarios and scaling the effect of the progressive implementation of these scenarios on sustainability against the business-as-usual forecast.

1.3 Literature review

The focal point of this review is the origin and comprehensiveness of the references models which are based on the classic concept of WtW modelling which although necessary is not directly usable in strategic planning without standardization. Some studies acknowledged the

importance of standardization without naming it and these will be discussed. To optimize the richness of the information embedded in the STM the most acknowledged, recent and comprehensive models in the field which collate a numerous number of focussed studies and expand on previous models are used.

1.3.1 Reference models

1.3.1.1 Argonne National Laboratory (ANL)

In 1995, with funding from the US Department of Energy (DOE) the ANL began to develop a spreadsheet based model for estimating the full life cycle energy and emissions impacts of alternative transportation fuels and advanced vehicles technologies (Wang, 1996). The model, called GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) was released in 1996 and since then there have been regular updates and upgrades to the model. The most recent version for fuel cycle analysis is GREET v1.8c0 which was released in 2009 and is publicly available free of charge (see http://greet.es.anl.gov/main). For the current study, we widely use GREET v1.8c0 (ANL, 2009) which was disintegrated and incorporated into the STM. The GREET v1.8c0 model calculates the fuel cycle energy consumption and emissions for various transportation and vehicle technologies. For energy consumption GREET calculates consumption of total energy, fossil fuels, petroleum, coal and natural gas. For emissions GREET calculates emissions of GHGs (primarily CO_2, CH_4 and N_2O) and six criteria pollutants (VOCs, CO, NO_x, PM10, PM2.5 and SO_x). In GREET the emissions factors for different combustion, chemical and petroleum processes are derived from the Environmental Protection Agency (EPA) AP-42 documents (EPA, 1995). More details on the structure of GREET is found in Chapter 2.

The GREET model is very comprehensive and builds on the earlier LCA models of National Renewable Energy Laboratory (1991, 1992), Bentley (1992), Brogan and Venkateswaran (1992), Ecotraffic, AB (1992), Wang and Santini (1993), Darrow (1994b, 1994a), Accurex (1996) and Delucchi (1991, 1993, 1997). As a matter of fact the early work on GREET, as documented in (Wang, 1996), relied heavily on methodologies used and data presented in Delucchi's 1991 study which was the most comprehensive study of fuel cycle GHG emissions at that time. Moreover, GREET formed the main data source for various studies and models such as the WtW model developed by TIAX LLC for California Energy Commission (Unnasch and Pont, 2007) and the General Motors (GM) North American WtW study which was conducted with ANL (GM *et al.*,

2001; GM *et al.*, 2005) and served as an important reference for the worldwide discussion on energy consumption and GHG emissions caused by traffic. Also GREET v1.6 (Wang, 2001) contributed to the development of the most recent UK based life cycle assessment of vehicle fuels and technologies by Ecolane Transport Consultancy (Lane, 2006).

1.3.1.2 General Motors (GM)

The North American GM WtW study which employed the GREET model provided the basis for the even more comprehensive European WtW study which was presented to the public in May 2002 (GM *et al.*, 2002b). The development of the European model employed the E2 database tool of the Ludwig Bölkow Systemtechnik (LBST) research institute in Germany which was the scientific advisor for the study. The E2 database evaluates the GHG emissions (CO_2, CH_4 and N_2O) and energy consumption of 44 WtT pathways. BP, Exxon Mobil, Shell and TotalFinaElf provided their "know how" as energy companies for the WtT calculations. The TtW calculations (when the vehicles are used) were made by General Motors (GM). This model is a well-recognized benchmark in the field and was completely incorporated into the STM. Recently this model was used for further WtW analyses such as the study performed by Lopez *et al.* (2009) on the GHG emissions of refuse trucks in the City of Madrid.

The conclusions of the GM European study (GM *et al.*, 2002b) point to some important facts such as that of *"Biomass-derived fuel pathways show the highest complexity and the widest range of results depending on applicable cultivation method, fertilizers use, soil and climate conditions"*, yet the mentioned study does not account for the GHG emissions linked to land use change which would add more to the complexity of the results. However, from a critical view it is seen that the authors of the mentioned study repeated the common mistake of looking at the apparent benefits of hydrogen relative to the reference chain (i.e. petrol chain) when they stressed on the renewably-produced hydrogen in combination with fuel cell vehicles as an effective strategy for significantly lowering GHG emissions and improving fuel supply diversity and turned a blind eye to the competing alternatives such as the direct use of renewable electricity in combination with battery electric vehicles.

1.3.1.3 European Commission (JRC), EUCAR and Concawe

The above mentioned GM European model was part of the historical background of the work started in 2002 by the JEC consortium which was formed from the Joint Research Centre of the European Commission (JRC), EUCAR (auto industry) and CONCAWE (refining industry) for the evaluation of the WtW energy use and GHG emissions for a wide range of potential future fuels and vehicles options (Edwards *et al.*, 2007). The CONCAWE/JRC group was assisted by LBST on the WtT part of the work so allowing access to the database of the previous work with GM (GM *et al.*, 2002b) and providing the E3 database tool which can estimate the macro-economic costs of fuel pathways in addition to the energy consumption and GHG emissions (LBST, 2008). The first version was published in December 2003 and the version incorporated into the STM (version 3) was released in December 2008 (see http://ies.jrc.ec.europa.eu/jec-research-collaboration/downloads-jec.html). The JEC study is now used by many as the reference study in the EU. "The JEC consortium advised the EU Commission and supplied data for the development of the Renewable Energy Directive GHG methodology and default values" (Larivé, 2009). Among the studies that used data from the JEC model is the report on the future road fuels by the UK Petroleum Industry Association (Bishop and Watson, 2004), the life cycle assessment of vehicle fuels and technologies by Ecolane Transport Consultancy in the UK (Lane, 2006) and the study on the comparison of various biofuels by Ecotraffic in Sweden (Ahlvik, 2008).

1.3.1.4 University of California, Davis

In this section the Lifecycle Emissions Model (LEM) of Mark Delucchi, who is a research scientist at University of California Davis, is discussed. In 1991, Delucchi completed a study to estimate fuel-cycle emissions of GHGs for various transportation fuels based on a Lotus software spreadsheet model (Delucchi, 1991, 1993). The model focuses on standard GHGs (CO_2, CH_4 and N_2O) and also includes some criteria pollutants (CO, NO_2, and NMOG). As mentioned above at that time Delucchi's study was the most comprehensive study of fuel cycle GHG emissions. Delucchi has continued to revise and upgrade his model by broadening inputs and outputs, updating data assumptions and structure, and adding sources of emissions. The most recent report published by Delucchi is the one in 2003 (Delucchi, 2003) which provides full documentation of model assumptions, scope, equations and results. LEM exists in a spreadsheet

form that is not publicly available. The data incorporated into the STM was extracted from Delucchi (2003, 2005).

Also the STM took advantage of the expanded work of Delucchi on the LEM which had adapted the structure and data specifically to Canada. This version served as the basis of what is called today the GHGenius model. A number of changes were made to that version to produce the GHGenius model, most important of which was including additional fuel pathways; these include the pathways of ethanol from sugarbeet and sugarcane. Nevertheless, the LEM and GHGenius models remain very similar internally. The GHGenius model is available as a free, open source Excel spreadsheet program which does not provide a user interface outside the one provided in the Excel spreadsheet. The STM expanded the data from Delucchi's work by incorporating data of sugar ethanol pathways from GHGenius v3.15 ((S&T)^2 Consultants Inc., 2009) which can be obtained online (see http://www.ghgenius.ca/). In chapter 2 the structural limitations of data from LEM and GHGenius are discussed.

The difference between GREET and Delucchi's model was first studied by Andress (1998) for the ethanol fuel cycles in which some general similarities and differences are addressed. However, recently Warner (2009) performed a more general comparison between GREET and Delucchi's models (including the GHGenius model) in terms of scope, fuel pathways, emissions tracked and data sources. Of particular interest in Warner's review are the differences in the data sources of the mentioned models. According to Warner (2009) there are some basic data sets common between the GREET and Delucchi's models, such as the Department of Energy (DOE) and the US EPA AP-42 emissions factors list, however the main differences between the data sources of the mentioned models is that GREET has a greater emphasis on stakeholder input and the use of data generated from literature review, models and simulations, whereas Delucchi's models establish a hierarchy of acceptable data with models and simulations placed low on the list. The Delucchi's models are more focused on scientific experiments, other EPA documents and engineering design data, and plants in operation.

1.3.1.5 The European Fuel Cell Forum

In 2003, authors from Switzerland and UK lead by Ulf Bossel, the head of the European Fuel Cell Forum, published a study on the future of the hydrogen economy based on an eco-efficiency

model and the most recent revision of this study was made in 2005 (Bossel *et al.*, 2003). Although the model is focused on the renewably-produced hydrogen pathways and is not very comprehensive it represents strongly discouraging conclusions for the hydrogen economy and triggered strong responses from the promoters of hydrogen fuel including LBST in Germany. As a matter of fact the comments of LBST on the paper by Bossel *et al.* in a paper published in 2003 (Weindorf *et al.*, 2003) present a sound criticism by pointing on some major weaknesses in the approach such as the failure to consider the high efficiency of hydrogen vehicles using fuel cells and the omission of an account of the environmental impacts.

Nevertheless, as the Bossel *et al.* (2003) study has aroused interest in various groups and at various levels contradicting the common view of a number of comprehensive industry-led projects and presented sound assumptions and calculations that rely on solid physics and data from direct communication with industry for the energy side it was deemed worthy to be incorporated into the STM along with the giants in the field. The aim of the STM is not to get indulged in the non-productive debate that is triggered by the different expert systems but to create a consensus among the best and overcome the barriers that forbid the effective use of LCA in strategic planning.

1.3.1.6 Öko-Institut (Institute for Applied Ecology)

Since 1987, Öko-Institut (Institute for Applied Ecology) in Germany developed a computerized life-cycle analysis model and database called GEMIS (Gesamt Emissions Modell for Integrierter Systeme). The first English version of the model called TEMIS (Total Emission Model for Integrated Systems) was developed in 1990 for the US DOE and a preliminary US database was established. Since then the model's use has expanded globally and a similar work to that with the US DOE was carried out for Italy, Turkey, and the UK including the ICLEI's (Local Governments for Sustainability) Urban CO_2 Reduction Project (see http://www.iclei.org/index.php?id=800). In 1994, the so-called EM (Environmental Manual for Power Development) was developed for German GTZ[3], and the World Bank to extend the scope of the GEMIS model, and its database to developing countries. In late 2000, Öko-Institut

[3] International cooperation enterprise for sustainable development with worldwide operations (http://www.gtz.de/en/)

introduced the improved, multilingual version 4.0 which integrates all previous daughter models into one single software which is today also called GEMIS but the acronym now stands for Global Emissions Model for Integrated Systems (Fritsche, 2001).

The GEMIS technology data (e.g. efficiency, auxiliary power use, etc) come from industry sources, life cycle studies, and national or UN statistics and have been cross checked with other studies. Emissions data comes from GHG inventories, technology assessment studies, operation experiences, specifications of manufacturers, and environmental standards, based on German, EU, US EPA/DOE and IEA/OECD sources. For developing countries data, case studies and applications have been carried out, and national as well as utility data were the basis for the country datasets (Fritsche, 2001).

The author is confident to say that GEMIS is the most global and comprehensive LCA model and database today and can evaluate the environmental impacts of an unprecedented number of energy, material and transport systems or any sectoral or cross-sectoral subsystem (e.g. a plant, facility, or special life cycle) at local, regional, national and global levels, i.e. air emissions (SO_2, NO_x, particulates, CO, HCl, HF, H_2S, NH_3, NMVOC), GHG emissions (CO_2, CH_4, N_2O, HFC, PFC, SF_6), liquid effluents (AOX, BOD, COD, N), solid wastes (ashes, etc) and land use. The GEMIS database is the most relevant part of the model offering more than 4500 processes, and covering more than 30 countries. The GEMIS model family is used in OECD countries including UK and US, more than 20 developing countries including China and India and Central/Eastern Europe including Russia. It has been used as a reference in building other databases such as the E2 and E3 databases by LBST.

The most recent version of GEMIS v.4.5 (Öko-Institut, 2008) was widely incorporated into the STM by creating hundreds of processes relevant to the systems under study, building the system models, running the calculations and extracting data. That would not have been possible without access to the model software which is made publicly available by Öko-Institut as free of charge (see http://www.oeko.de/service/gemis/en/material.htm). More details on the structure of GEMIS are found in Chapter 2.

1.3.2 Studies excluded

The models incorporated into the STM as presented above include only major, original, comprehensive and most recent analyses of life cycle emissions and energy consumption from a wide range of alternative transportation fuels (see study scope and pathways in Chapter 2). These models together generate an extremely rich fund of information and promise high level of confidence in the results. The STM does not directly include the following: (i) older LCAs of alternative transportation fuels such as Ecotraffic AB (1992), Gover *et al.* (1996) and ADL (1996), (ii) studies that are entirely derivative such as Koroneos *et al.* (2004), which is derived from GEMIS database and Spath and Mann (2001), (iii) studies of a single fuel or narrow range of transportation fuels such as Macedo (2004), Elsayed *et al.* (2003), Spath and Mann (2001, 2004), Binder *et al.* (2005), Hekkert *et al.* (2005) and Gnansounou *et al.* (2009), (iv) studies that focus mainly on the life cycle of the vehicle as opposed to fuels and (v) studies that do not provide the data transparency required for standardization such as CVTF (2000), Weiss *et al.* (2000) and Hackney and Neufville (2001).

The CVTF (2000) study on the potential of alternative road fuels and vehicle technologies was completed by the Cleaner Vehicles Task Force which involves the Energy Savings Trust (EST), Ecolane Transport Consultancy, Energy Technology Services and Department of Environment, Transport and the Regions (DETR) to evaluate the potential benefits associated with cleaner petrol (<50 ppm sulphur), natural gas (NG), battery electric vehicles (BEV), hybrid electric vehicles (HEV), fuel cell vehicles (FCV), among other alternative fuels and technologies. This UK based study builds on early LCA work by the Energy Technology and Support Unit (Gover *et al.*, 1996) of AEA Technology which was the first of its kind in the UK and an expansion to an earlier impact model developed at AEA Technology, Eyre and Michaelis (1991). It formed the basis of the Tyndall Centre study on the role of hydrogen in powering the road transport (Pridmore and Bristow, 2002) and contributed for the development of the recent LCA of vehicle fuels and technologies by Ecolane Transport Consultancy (Lane, 2006). However, although the CVTF (2000) report provided an annex of data with references, no access to the model itself was given and no breakdown of the data associated with the fuel WtT chain was provided which prevented the incorporation of the model into the STM.

The same limitation applies to Hackney and Neufville (2001) who presented an extension of the early model by Arthur D. Little (ADL, 1996) completed for the Ford Motor Company. Neither the original report by ADL nor the spreadsheet of Hackney's model is available in the public domain. Furthermore, the complete documentation of Hackney's model (Hackney, 1997) does not provide a breakdown of the data so preventing incorporation into the STM.

The report on the well cited MIT model for the assessment of different fuels and vehicle technologies in terms of energy consumption, GHG emissions and costs for the year 2020 provides transparent calculations and assumptions, however, unfortunately, the WtT data is not disclosed in a broken down structure and no access to the model itself is given (Weiss *et al.*, 2000). Nevertheless, the TtW data of the MIT model is provided with good transparency and represent an optimistic view of the future. This was incorporated into the STM to give a more complete picture of what we should expect in a dynamic World. Therefore the TtW data from (Weiss *et al.*, 2000) is embedded in the STM.

1.3.3 Important observations

In this section the progressive recognition of the transport LCA community to the importance of the standardization is tracked. A distinction is made between standardization and the requirement of integrating a stochastic application only to address the uncertainty of the input parameters with no change in the elements of the model. In late 90s the LCA community started to practically address uncertainties attached to the principal input parameters of the model led by the incorporation of Monte Carlo simulation in GREET version 1.6 using a commercial software Crystal Ball™ developed by Decisioneering, Inc. (Wang, 2001). This feature was developed during the project that Argonne conducted for General Motors Corporation's (GM's) Global Alternative Propulsion Center (GM *et al.*, 2001). Later a new sophisticated stochastic simulation capability was developed for GREET by Vishwamitra Research Institute (VRI) and that is described in the article of Subramanyan *et al.* (2008). Following the first step by ANL during the project with GM stochastic applications were incorporated in the MIT model (Weiss *et al.*, 2000), the GM European model (GM *et al.*, 2002b) and others until today when nearly all LCA tools can address uncertainties in input parameters. In this respect, Contadini (2002) in his PhD thesis claims to be the first to perform a quantitative uncertainty analysis as suggested by ISO 14041 (1998) using probabilistic curves generated by experts.

Nevertheless, the problem that is being tackled in this project is not limited to the uncertainties of the input parameters. Also the methods used before to address uncertainties, even if involving experts and complying with ISO standards, do not necessarily increase the reliability of the output results simply because the probabilistic curves are subjective and restricted to the perspective or view of one group. The problem the STM is in fact tackling is the management of the actual uncertainties linked to changes in the elements of the model including structural assumptions, choices and expert groups. In fact the LCA community has been circulating around this problem and very recently some quiet sounds have reflected the importance of addressing this new level of uncertainty but a solution has yet to be presented.

Michael Wang of ANL has made an important statement in 1998 when he said: *"parametric assumptions change frequently from studies to studies or from time to time with a same study, as such comparison of results among studies is less meaningful (Wang, 1998)."* In this statement Wang did not only present a problem of comparability but also indirectly admitted the problem of usability. When results of WtW analysis are not comparable under changes in the elements of the model, they are indeed not usable for making strategic decisions where the stability of the output is crucial. A clearer statement was made by the International Energy Agency (IEA) in their assessment and comparison of alternative transportation fuels in search for ultimate fuel (IEA, 1999): *"No single reference can adequately describe the chain in terms of energy consumption and GHG emissions. Different situations cause differences in fuel chains analysis. For instance, crude oil for European refineries may come from either the Middle East or the North Sea, whose proximity reduces energy consumption for feedstock transport."* This statement meant that no single model should be used to make a decision and acknowledged the problem of using fuel chain analysis with default assumptions in policy making. In fact the early IEA assessment was survey based and did not involve any kind of modelling. It was based mostly on the earlier series of Automotive Fuels Surveys from IEA Automotive Fuels Information Service (AFIS) from 1996 and 1998 which is no longer available in the public domain. The IEA (1999) report provides no basic data and the WtW results are expressed as ranges that provide no insight into the origin of the results and how the information is clustered. Nevertheless, the IEA assessment presents a clear, sound breakdown of the fuel chain into 4 stages and that was adopted in the structure of the STM (see Figure 2.1 of Chapter 2).

However, during the course of the research especially very recently others have started to address the same problem. These stirrings mainly stem from the surging controversy in literature over the net benefit of biofuels. In this respect Cherubini *et al.* (2009) in their work on the key assumptions and methodological choices in biofuels LCA made a very important intervention: *"LCA results based on selected default values and simple allocation may significantly increase the risk of drawing misleading conclusions. Some of the key parameters vary widely between systems and locations, and many are subject to remarkable uncertainties. Thus, there is a high probability that the true energy balance and GHG emissions for a specific system will be substantially different from the default results. Consequently, uncertainty and sensitivity analysis should be presented with ranges that take into account all the different assumptions and variables."* Similarly acknowledged by Gnansounou *et al.* (2009) which expanded the work of various authors who have demonstrated the significant effect of methodological choices on the GHG and energy balance of biofuels through review papers and other similar studies (Farrell and Sperling, 2007; Börjesson, 2009) by what they claim to be a quantification of these effects. Nevertheless, neither the ranges of the results presented by Cherubini *et al.* (2009) which are elaborated from the software tool GEMIS nor the ranges of the results presented by Gnansounou *et al.* (2009) which were based on a case study concerned with the production of fuel ethanol from wheat in the Swiss context are an actual quantification of the effects of variation in the methodological choices amongst other modelling elements. These ranges such as those depicted in Table 1.1 for three selected options are only a demonstration of the effect of changes in the modelling elements and indeed cannot be claimed to be a quantification of the resulting uncertainties.

The range is a portfolio which is strictly used to demonstrate the impact of changes in the modelling elements on the result but is not statistically valid, nor does it provide an insight into the probability distribution and does not allow the type of sensitivity analysis which relates the variability of the result to the contribution of different factors. Also as uncertainties are not stochastically measured and described, any relationship between the resulting portfolios cannot be described and embedded in the analysis.

This project presents the STM which pioneers in many areas including (i) the stochastic measurement of uncertainties under the effect of changes in the modelling elements including

changes in the expert groups, (ii) the identification of the major sources of disagreement within the expert systems, (iii) the ability to undertake statistical analysis of the results including the correlation of the alternative and reference systems, and (iv) the focus on the global benefits of alternative transport systems rather than only looking through the window of the transport sector. Nevertheless, the standardization of the major WtW models is not straightforward due to many difficulties including (a) the understanding of complex data inventory and the structural differences between different models, and (b) the lack of access to the model software and provision of data breakdown. In fact, no method of standardization is available in the UK or internationally and this project presents a new important initiative in the field. Also many authors talk about the difficulty of comparing results from different studies where Geerken *et al.* (2004) in his review of the LCA studies said: *"The final results from different studies with different assumptions are often not easy to compare, because of differences in scope (chosen impacts), reference year of technology, geographical differences, system boundaries, …"* On the same line Gnansounou *et al.* (2009) said: *"quantitative investigations of the differences in the results from one study to the other are not straightforward due to the lack of information concerning inventory data, the assumptions made to complement unavailable data and modelling choices about system definition and boundaries, functional units, reference systems and allocation methods."* In the research presented in this project, the largest possible assessment platform was developed to compare the data from the major models in the field including an investigation of the sensitivity of the results to several factors.

1.4 Thesis structure

In this chapter the general drivers for research in the context of sustainable energy was discussed and the area of our work was specified. The concept of source-to-use analysis was introduced and some chains were presented diagrammatically for non-experts in the field to see the boundaries of this type of analysis. Much of the writing in this chapter focused on presenting the problem of LCA usability in transport policy making and our contribution in this respect by the development of the Standardization Transport Model. The nature of the STM results was described to show the difference from the results of classic models and present a solution to the problem. The literature review forms part of this chapter and focused on the reference models which were used in the standardization process.

In Chapter 2 the goal and scope of this project including the WtW chains under assessment are defined and the structure of the STM and what it measures are presented. The methodology of the data work is discussed in detail with demonstrations of the different structures of WtW modelling and databases.

The statistical methods of the standardization process form the subject of Chapter 3 which presents the nature of the STM results in statistical terms, defines the target population of the STM and explains every method in the statistical part of the methodology starting with the compilation of data and characterization with mathematical functions and ending with the Monte Carlo simulation. This chapter is dedicated to the understanding of the statistics applied in the model and maybe omitted at first reading.

Chapter 4 is part of the results analysis and discussion in which the uncertainty of the STM results is probed by appropriate sensitivity analysis. Prior to the development of the STM it was not possible to relate the uncertainty of the output from the differences in the modelling elements to the major factors of variability simply because classic WtW models do not allow for the variability of modelling elements. The sensitivity analysis in this project involves qualitative sensitivity analysis which presents the first comprehensive platform of comparison between the expert systems in the field. The outcome of sensitivity analysis summarizes the major sources of variability which form points of focus in the optimization of the output results including the minimization of the risk of energy and GHG emissions debt.

In Chapter 5 the results of the STM are presented and comparative analysis based on well defined criteria is performed. The output portfolios are statistically valid, have mathematical character and related to the variability of the modelling elements by sensitivity analysis. This allows for the correlation of the alternative systems with respect to the reference system and the generation of distributions of energy and GHG emissions change. Such distributions are the first of their kind by embedding the relationships between the alternative systems and the reference system in reality and improving the comparison of different alternative systems. The outcome of this analysis produces a consensus among the energy research community and paves the way for the development of a strategic framework for carbon and energy reduction in transport.

Chapter 6 is a supplementary chapter developed in the course of this project to open a new debate in the energy field and draw a new boundary for transport systems analysis. This work seeks to improve the practical use of the LCA tool in strategic planning and delivers a very important message to analysts of transport systems: *"The World needs a sustainable energy system and not a sustainable transport system."*

Following the results analysis and discussion and the analysis of a new boundary for transport systems analysis a set of rules which shape a framework for carbon and energy reduction in passenger cars transport is produced. Chapter 7 presents a UK-based study which places the results of the STM and the analysis of the synergistic behaviour between the transport and power sectors into perspective. The framework is translated into various scenarios of the future of passenger cars transport in the UK and the effect of implementation is scaled against the business-as-usual scenario. This type of future study is the first to follow a robust framework and not an arbitrary target such as simply 60% CO_2 reduction by 2050.

Those wishing to move rapidly to the output of the STM may omit the thorough explanation of the standardization process which begins with Section 2.4 and includes the whole of Chapter 3. Also, at first reading, one may move to Section 4.4 which summarizes Chapter 4.

2 Goal, Scope and Methodology

2.1 The Well-to-Wheel model

The Life Cycle Analysis (LCA) process is a systematic, phased approach which has several possible users and uses. The power of the LCA tool in analyzing the impact caused by a product or process during its entire life cycle from production, through use, to disposal makes it ideal for comparing competing products or processes. Nowadays LCA forms the foundation of the new field of industrial ecology. However, the word "impact" is abstract and can refer to many types of effects. As such an LCA tool can only be modelled if a clear goal and scope is defined to establish the context in which the assessment is to be made and identify the boundaries and environmental effect to be reviewed for the assessment.

The so-called 'cradle-to-grave' or 'well-to-wheel' (WtW) analysis is a model of LCA widely established and used to assess competing transport systems in terms of pre-defined dimensions (e.g. GHG emissions). Although the LCA and WtW analysis notions are often interchanged in the literature, they are different in terms of scope, boundary, and impacts.

The WtW analysis is often specifically aimed at transport applications, whereas LCA is a general methodology that can be applied to any kind of system or product. Nonetheless, WtW analysis typically focuses on the production and distribution of different fuels and on the emissions of vehicles during use. LCA typically focuses on both the life cycle of products (e.g. fuel) and product systems (e.g. vehicle). Applied to transport, this typically includes the three phases of a vehicle (production, use and disposal) and also the production and distribution processes of the needed fuel (e.g. gasoline). On the other hand in terms of impacts, WtW studies typically include GHG emissions (mainly contributions from CO_2, N_2O and CH_4) and an energy (efficiency) indicator. On the other hand, LCA studies usually include more impact categories than WtW studies, such as acidification, entrophication, ozone layer depletion, carcinogenics, etc. Last and not least, in terms of data sources WtW studies typically have good access to primary data sources (from suppliers/producers); whereas LCA studies typically make use of both primary and secondary data from literature (Geerken *et al.*, 2004).

It is seen therefore that an LCA study is more suitable for assessing a certain process operation (e.g. refinery). However, when it comes to *comparatively* assessing a series of different transport options with the aim of reducing certain impacts, for instance the reduction of carbon emissions

and energy consumption in transport, a WtW study is more practical in terms of focus, scope and impacts.

2.2 Goal definition

Most of the WtW studies today do not perform strategy analysis but rather present the differences between some specific existing and some selected future transport options based on certain measured dimensions (e.g. GHG emissions). On the other hand, the goal of the STM is to generate standardized WtW results, the nature of which was outlined in Chapter 1, for various transport chains. The key outputs for each chain are: (i) the total energy consumption in the form of Mega Joules per kilometre (MJ/km), and (ii) the total GHG emissions in the form of grams of carbon dioxide equivalent per kilometre (gCO_2eq/km). The outcome of the comparative analysis based on the standardized results is aggregated into a strategic framework which is necessary to facilitate the concentration of research efforts and investments on the true options of tomorrow.

However, in using the STM in strategy analysis it is unclear as to which criteria are most appropriate for comparative analysis of the WtW outputs especially as different options may use different types of resource. For instance, a common conclusion is that option A is generally more energy efficient than option B; what would this imply knowing that the two options may use different types of resources such as renewables and non-renewables.

Today it is surely true that the principal criterion of comparison between different options based on the standardized results is *sustainability* in its energy and environmental perspectives. A sustainable action was defined by the United Nations General Assembly in the late 80s as: *"that which meets the needs of the present without compromising the ability of future generations to meet their own needs (UNGA, 1987)."* The framework aims for increases in sustainability by reducing losses and dependence on exhaustible type of energy resources such as fossil fuels and hence reduce the global impact of Global Warming.

2.3 Scope of analysis

2.3.1 The structure of the STM

As seen in Figure 2.1 below an STM chain is divided up into 5 building blocks which are summed up into two linked energy stages: (i) the production and distribution of fuels, commonly known as the Well-to-Tank (WtT) chain and (ii) the vehicle operation, commonly known as the Tank-to-Wheel (TtW) stage. The former includes:

1- Feedstock Production (SP): This includes all the steps between the well and the outlet of the feedstock production site (e.g. the recovery and processing of natural gas);
2- Feedstock Transport (FT): This includes all the steps between the outlet of the feedstock production site and the inlet of the fuel production site (e.g. the liquefaction, maritime transport, re-gasification and distribution of natural gas);
3- Fuel Production (FP): This includes all the steps between the inlet and the outlet of the fuel production site (e.g. the steam methane reforming –SMR- of natural gas into gaseous hydrogen);
4- Fuel Distribution (FD): This includes all the steps between the outlet of the fuel production site and the vehicle tank (e.g. the pipeline distribution, compression, storage and dispensing of hydrogen into a fuel cell vehicle tank).

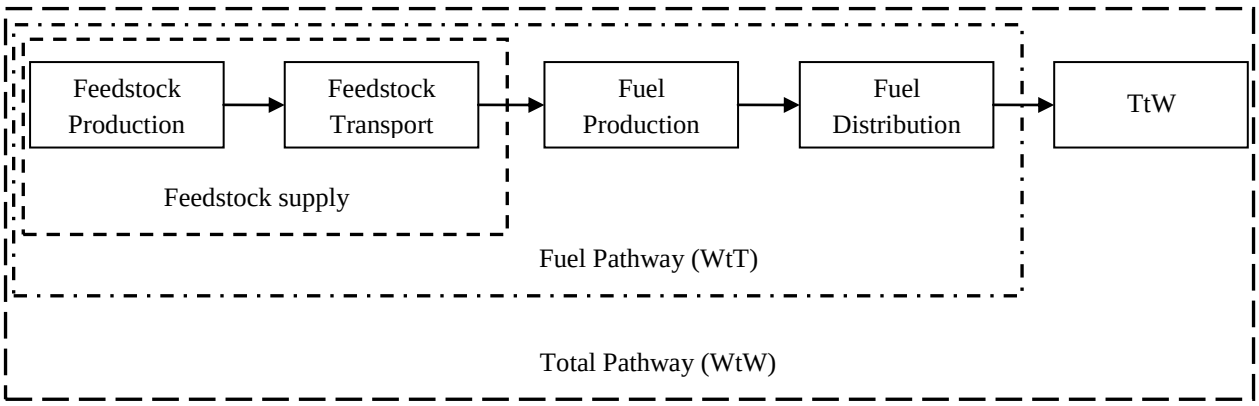


Figure 2.1: The structure of the standardization transport model (STM)

For each of the above building blocks, the STM combines the different system assumptions (e.g. the energy consumption for fuel production) embodied within the reference models (i.e. GREET, GEMIS, JEC, etc). The process by which this is done is outlined later in Section 2.4. The system

assumptions associated with the WtT stages such as feedstock production and fuel distribution are sampled in the form of unit energy or else unit GHG emissions per 1 MJ of fuel throughput (e.g. MJ/MJ_{fuel}). And the system assumptions associated with the TtW stage are sampled in the form of unit energy or else unit GHG emissions per 1 km when the desired model output is per 1 km (e.g. MJ/km). On the other hand the system assumptions associated with the TtW stage are sampled in the form of unit energy or else unit GHG emissions per 1 MJ of work done (that can be a drive or any type of work) when the desired model output is per 1 MJ of work done (e.g. MJ/MJ_W). (Later the author will show why the model output may be desired in a normalized form, i.e., for example in MJ/MJ_W.)

The STM sample data elements (e.g. x MJ/MJ_{fuel} for feedstock production) were not further factorized because as emphasized in Chapter 1 the sample should not be confined to the system assumptions embodied in one model. As different reference models such as GREET and JEC have different database structures, the form of the STM sample data elements was chosen so as to represent the common form that can overcome the structural differences between different models. It was also necessary to overcome the lack of data transparency of certain models. However this step develops dependencies between the variables of the STM. (As will be illustrated later in this chapter, such relationships are described and embedded in the simulation.)

2.3.2 The transport scope of the STM

As mentioned earlier in Chapter 1 the scope of the standardization in this project is limited to models for passenger cars (cars and taxis) and does not involve other modes of road transport such as LDV (Light Duty Vehicles) and HGV (Heavy Goods Vehicles).

2.3.3 The boundary of the STM

Although the vehicle life cycle is often included in transport WtW models such as in the study conducted by MIT (Weiss *et al.*, 2000) on the assessment of new automobile technologies, the present study does not consider the impacts (i.e. GHG emissions and energy use) embodied in the vehicle and only includes the vehicle operation as part of the total WtW chain as shown in Figure 2.1. This limitation stems from the author's belief that in a *comparative* life cycle assessment only processes (e.g. vehicle operation) which report a significant difference across different chains (e.g. gasoline from crude oil fuelled to an internal combustion engine vehicle)

should be considered. We support our assumption by using the results of a preliminary assessment of PEM fuel cell powered automobiles conducted by Hussain *et al.* (2007).

	GHG emission (tons CO_2)		**Energy consumption (GJ)**	
	PEMFC	ICE	PEMFC	ICE
Vehicle materials production	3.63	3.52	54.60	49.80
Vehicle assembly	1.65	1.76	24.30	25.50
Vehicle distribution	0.11	0.11	2.10	2.10
Vehicle use	0.00	59.03	195.00	819.00
Vehicle disposal	0.00	0.00	0.30	0.30

Table 2.1: A comparison of the life cycle for PEMFC and ICE vehicles (source: Hussain *et al.*, 2007)

As seen in Table 2.1 above, comparing the different elements of the fuel cell vehicle (PEMFCV) life cycle with those of the gasoline internal combustion engine vehicle (ICEV) life cycle shows no significant difference in terms of GHG emissions and energy consumption apart from the vehicle operation stage which is an integral part of the STM. Also it is noted that the GHG emissions associated with the vehicle disposal stage are approximations and do not represent realistic figures.

On the other hand, the STM draws a new boundary for the analysis of transport systems. All the major LCA studies on this subject such as that completed by General Motors Corporation (GM) in collaboration with Argonne National Laboratory (GM *et al.*, 2001), the European Union (GM *et al.*, 2002b), and others (Wang, 1998; Weiss *et al.*, 2000; Edwards *et al.*, 2007) restrict the boundary of the analysis to the transport system and ignore the synergies between the transport sector and other major sectors of energy resource use (e.g. power sector).

Such a view of the system is incomplete and cannot be relied on to build any future energy strategy. For instance, the implementation of one option for decreasing energy consumption and curbing carbon emissions in the transport sector may consequently cause a counter effect in the power sector which significantly decreases the expected reductions overall. This observation defines the scope of the current work which aims at looking outside the boundary of the transport system and assessing the synergistic behaviour between the transport sector and the power sector, the other major sector of fuel use. The analysis of such synergies is in Chapter 6 which is a supplement to the results analysis and discussion in Chapter 5.

This type of analysis involves variability in the fuel consumption systems between different sectors and thus the conventional units of the WtW results such as the GHG emissions expressed

in the form of grams of carbon dioxide equivalent per kilometre (gCO_2eq/km) in the transport sector and gCO_2eq/kWh in the power sector is not suitable for weighting the measured quantity (e.g. GHG emissions) across different sectors of energy resource use; one needs like-with-like. Thus the STM is also used to generate the measure of GHG emissions in the form of gCO_2eq per 1 MJ of work done (can be a drive or any type of work). Such a form of results is normalized to enable comparison of magnitude across different sectors of energy resource use.

2.3.4 Geographic scope and timeframe

Although the standardized transport model (STM), at least in its general form, lacks specificity of geographic scope and time frame this is seen as an advantage and not a disadvantage. According to a report of The European Organization for Packaging and the Environment (EUROPEN, 1999) on the use of LCA as a policy tool, one of the limitations of LCA in any policy or decision-making process is time specificity. An LCA study relates to one specific system at one defined point in time and thus would not reflect future changes that are not always apparent at the point when the study is conducted. For instance, take Europe and ask questions about whether one can be certain of how the energy supply mix looks like in 50 years from now?, or whether one can be certain of what will be the conditions of the supplying systems domestically and internationally in 50 years from now? The truth is that everything is variable and cannot be fully anticipated on the long run. Further, when it comes to technology any scope of sectoral or cross-sectoral subsystems (e.g., vehicle, plant, facility, etc) are traded as products across the globe.

This is a problem that cannot be resolved by classic WtW modelling which assumes default geographic location and time frame. In contrast, the results from the STM account for arbitrary changes in geographic location and time by combining established models. Thus the resultant STM buffers against future changes in geographic location of resources and time specific conditions (e.g. efficiency of resource extraction).

2.3.5 Chains

The following figures present the six types of pathways under consideration in the current study for various alternative transport systems. These are divided into crude oil based, Figure 2.6, which includes the conventional gasoline in ICE vehicle that represents the conventional chain,

NG-based, biomass-based, non-biomass renewables based and nuclear-based (Figure 2.2 to Figure 2.5), and coal-based (Figure 2.7).

The STM is designed with high flexibility to allow the inclusion of any factor of variability in the variables of the model including different process types and process designs among many other assumptions and choices, thus the STM can combine various classic WtW chains into one single chain to measure the uncertainty from the variation in the modelling elements. Nevertheless, each group of pathways under consideration as presented in Figure 2.2 to Figure 2.7 below is broken down into more than one STM according to the fuel type (e.g. CNG or CGH2), vehicle type (FCV or FC HEV), plant size[4] (onsite or central), process design (w/ CCS or w/o CCS), and/or feedstock type[5] (sugarcane or sugarbeet) to define the options under assessment. This led to the consideration of 48 different chains as listed below in Table 2.2 to Table 2.7.

Finally an important note is made: In strategic energy planning one compares *options*, e.g. NG to hydrogen fuel cell in a central system, and NOT specific *pathways*, e.g. NG from North Sea transported by HP pipeline over a specific distance to a central reformer followed by H_2 distribution by pipeline to a FC vehicle. The STM allows one to compare options whilst classic WtW models are confined to specific pathways. Unlike classic WtW models the STM is able to generate a single measure for impacts such as GHG emissions for an option under study.

[4] Not in all cases
[5] Only in the case of ethanol from biomass pathways

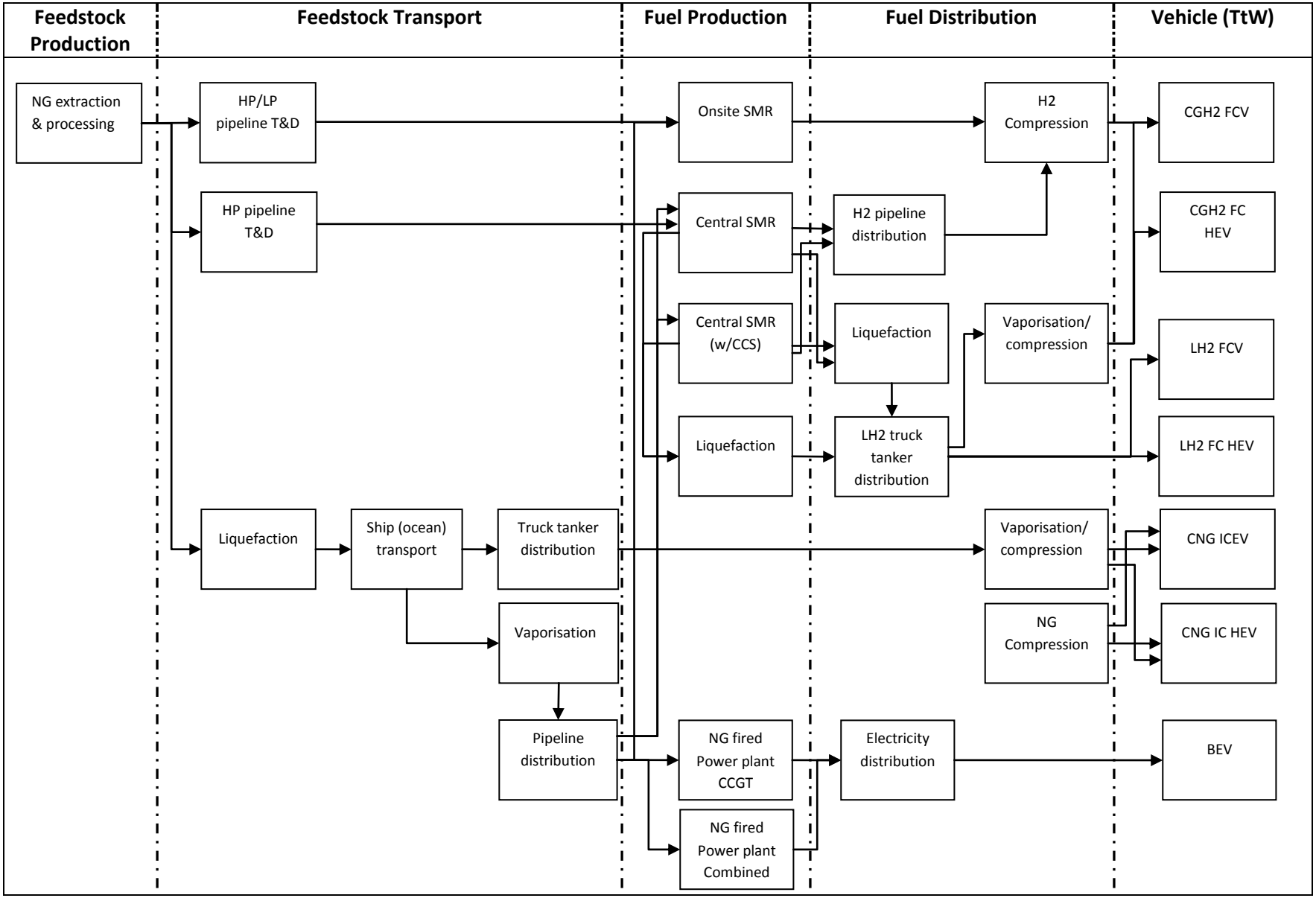


Figure 2.2: The NG-based pathways under consideration

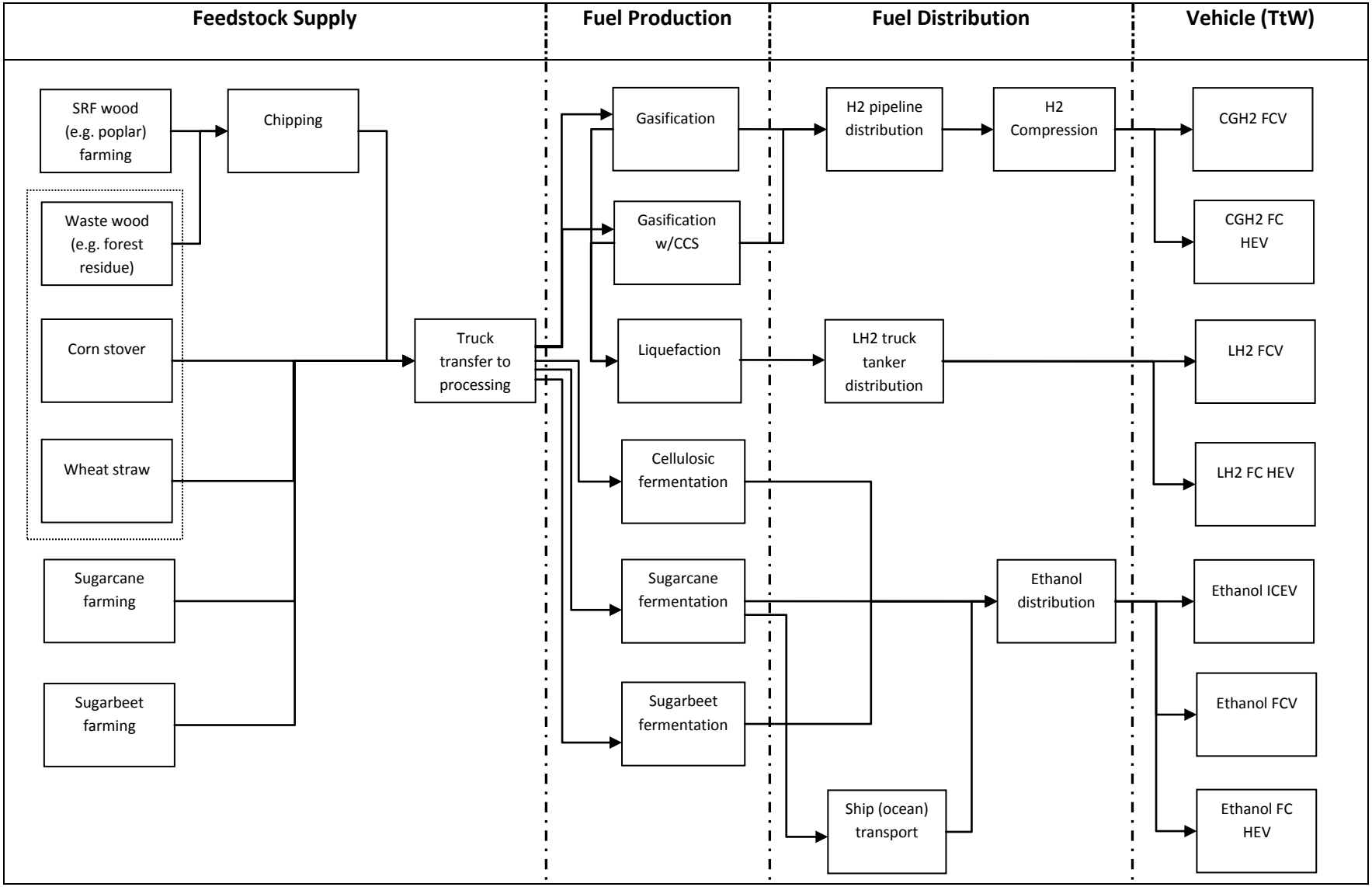


Figure 2.3: The biomass-based pathways under consideration

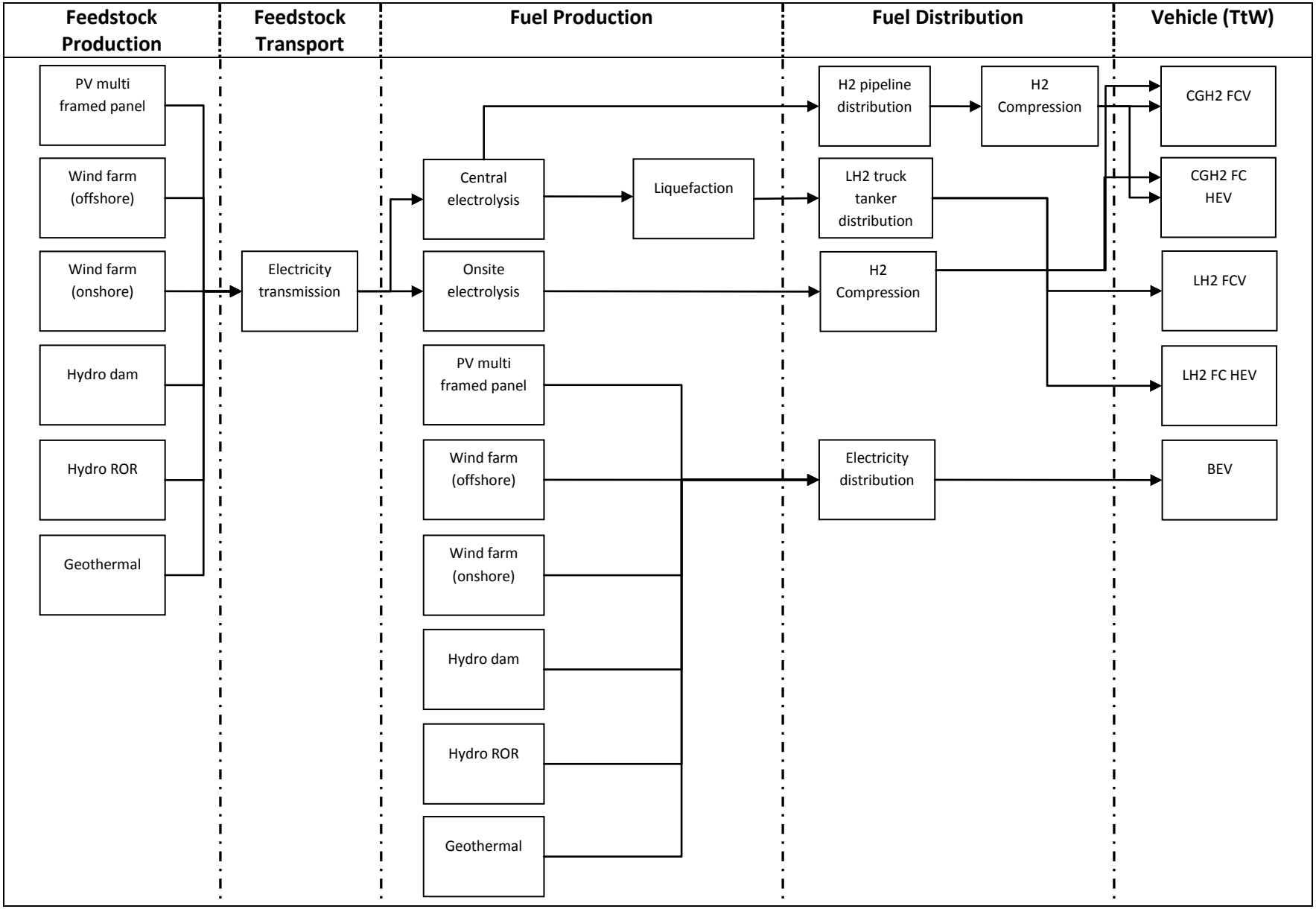


Figure 2.4: The non-biomass renewables-based pathways under consideration

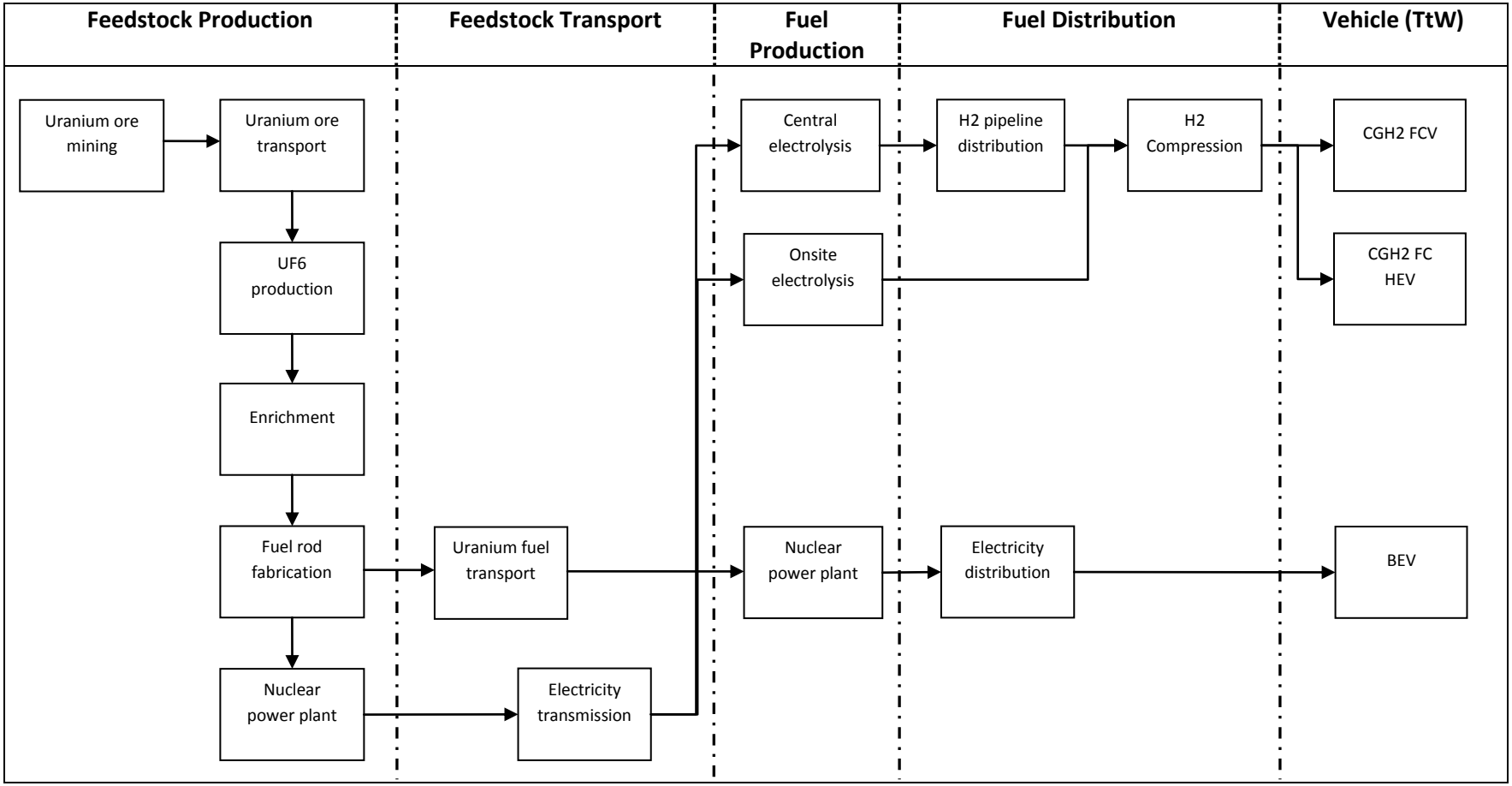


Figure 2.5: The nuclear-based pathways under consideration

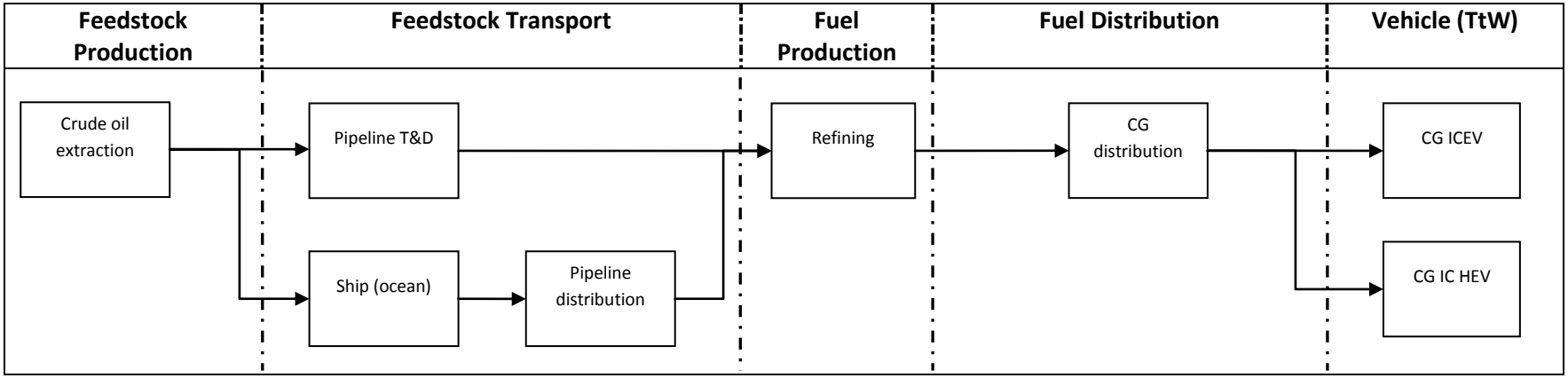


Figure 2.6: The crude-based pathways under consideration

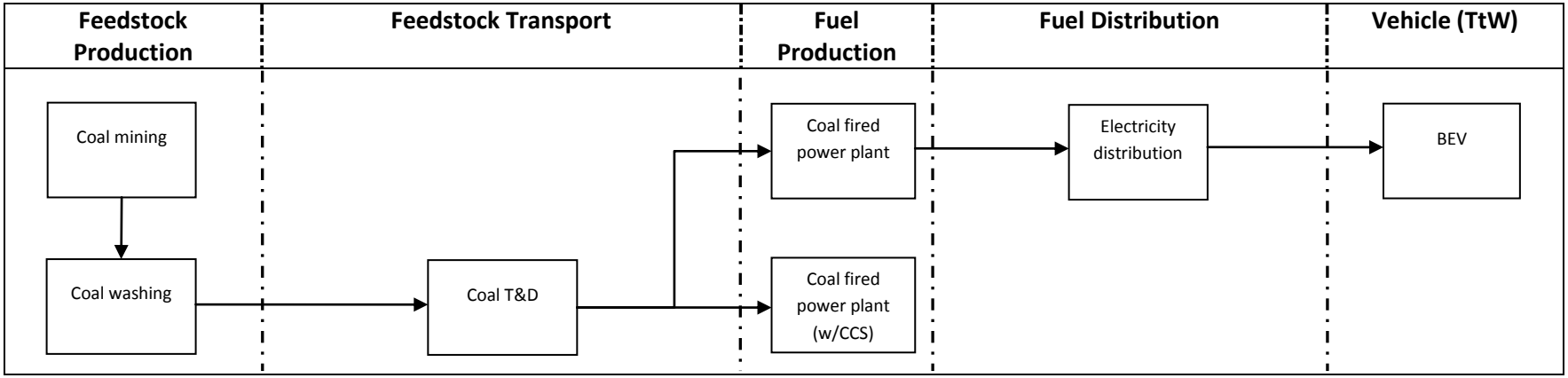


Figure 2.7: The coal-based pathways under consideration

From each group of pathways presented in Figure 2.2 to Figure 2.7 above the following options are defined. Each option represents one STM.

Table 2.2: The NG-based options under assessment

Chain	Feedstock	Fuel	Process	Vehicle
WtW-CGH2-NG-Central-FCV	NG	CGH2	Central SMR	CGH2 FCV
WtW-CGH2-NG-Central-FC HEV	NG	CGH2	Central SMR	CGH2 FC HEV
WtW-CGH2-NG-Central-w/CCS-FCV	NG	CGH2	Central SMR (w/ CCS)	CGH2 FCV
WtW-CGH2-NG-Central-w/CCS-FC HEV	NG	CGH2	Central SMR (w/ CCS)	CGH2 FC HEV
WtW-LH2-NG-Central-FCV	NG	LH2	Central SMR	LH2 FCV
WtW-LH2-NG-Central-FCV	NG	LH2	Central SMR	LH2 FC HEV
WtW-LH2-NG-Central-w/CCS-FCV	NG	LH2	Central SMR (w/ CCS)	LH2 FCV
WtW-LH2-NG-Central-w/CCS-FCV	NG	LH2	Central SMR (w/ CCS)	LH2 FC HEV
WtW-CGH2-NG-Decentral-FCV	NG	CGH2	Onsite SMR	CGH2 FCV
WtW-CGH2-NG-Decentral-FC HEV	NG	CGH2	Onsite SMR	CGH2 FC HEV
WtW-CNG-NG-ICEV	NG	CNG	N/A	CNG ICEV
WtW-CNG-NG-IC HEV	NG	CNG	N/A	CNG IC HEV
WtW-Electricity-NG-BEV	NG	Electricity	NG fired plant	BEV
WtW-Electricity-NG-w/CCS-BEV	NG	Electricity	NG fired plant (w/ CCS)	BEV

Table 2.3: The biomass-based options under assessment

Chain	Feedstock	Fuel	Process	Vehicle
WtW-CGH2-Biomass-FCV	Wood	CGH2	Gasification	CGH2 FCV
WtW-CGH2-Biomass-FC HEV	Wood	CGH2	Gasification	CGH2 FC HEV
WtW-CGH2-Biomass-w/CCS-FCV	Wood	CGH2	Gasification (w/ CCS)	CGH2 FCV
WtW-CGH2-Biomass-Central-w/CCS-FC HEV	Wood	CGH2	Gasification (w/ CCS)	CGH2 FC HEV
WtW-LH2-Biomass-FCV	Wood	LH2	Gasification	LH2 FCV
WtW-LH2-Biomass-FC HEV	Wood	LH2	Gasification	LH2 FC HEV
WtW-LH2-Biomass-w/CCS-FCV	Wood	LH2	Gasification (w/ CCS)	LH2 FCV
WtW-LH2-Biomass-Central-w/CCS-FC HEV	Wood	LH2	Gasification (w/ CCS)	LH2 FC HEV
WtW-Ethanol-Farmed-Wood-ICEV	SRF wood	Ethanol	Fermentation	Ethanol ICEV
WtW-Ethanol-Farmed-Wood-FCV	SRF wood	Ethanol	Fermentation	Ethanol FCV
WtW-Ethanol-Farmed-Wood-FC HEV	SRF wood	Ethanol	Fermentation	Ethanol FC HEV
WtW-Ethanol-Residual-Biomass-ICEV	Residue	Ethanol	Fermentation	Ethanol ICEV
WtW-Ethanol-Residual-Biomass-FCV	Residue	Ethanol	Fermentation	Ethanol FCV
WtW-Ethanol-Residual-Biomass-FC HEV	Residue	Ethanol	Fermentation	Ethanol FC HEV
WtW-Ethanol-Sugarcane-ICEV	Sugarcane	Ethanol	Fermentation	Ethanol ICV
WtW-Ethanol-Sugarcane-FCV	Sugarcane	Ethanol	Fermentation	Ethanol FCV
WtW-Ethanol-Sugarcane-FC HEV	Sugarcane	Ethanol	Fermentation	Ethanol FC HEV
WtW-Ethanol-Sugarbeet-ICEV	Sugarbeet	Ethanol	Fermentation	Ethanol ICV

WtW-Ethanol-Sugarbeet-FCV	Sugarbeet	Ethanol	Fermentation	Ethanol FCV
WtW-Ethanol-Sugarbeet-FC HEV	Sugarbeet	Ethanol	Fermentation	Ethanol FC HEV

Table 2.4: The non-biomass renewables based options under assessment

Chain	**Feedstock**	**Fuel**	**Process**	**Vehicle**
WtW-CGH2-Renewable-Electricity-Central-FCV	Ren. Elect.	CGH2	Electrolysis	CGH2 FCV
WtW-CGH2-Renewable-Electricity-Central-FC HEV	Ren. Elect.	CGH2	Electrolysis	CGH2 FC HEV
WtW-LH2-Renewable-Electricity-Central-FCV	Ren. Elect.	LH2	Electrolysis	LH2 FCV
WtW-LH2-Renewable-Electricity-Central-FC HEV	Ren. Elect.	LH2	Electrolysis	LH2 FC HEV
WtW-CGH2-Renewable-Electricity-Decentral-FCV	Ren. Elect.	CGH2	Electrolysis	CGH2 FCV
WtW-CGH2-Renewable-Electricity-Decentral-FC HEV	Ren. Elect.	CGH2	Electrolysis	CGH2 FC HEV
WtW-Electricity-Renewable-BEV	N/A	Electricity	Power system	BEV

Table 2.5: The nuclear-based options under assessment

Chain	**Feedstock**	**Fuel**	**Process**	**Vehicle**
WtW-CGH2-Nuclear-Electricity-FCV	Nuclear Electricity	CGH2	Electrolysis	CGH2 FCV
WtW-CGH2-Nuclear-Electricity-FC HEV	Nuclear Electricity	CGH2	Electrolysis	CGH2 FC HEV
WtW-Electricity-Nuclear-BEV	Uranium	Electricity	Nuclear plant	BEV

Table 2.6: The coal-based options under assessment

Chain	**Feedstock**	**Fuel**	**Process**	**Vehicle**
WtW-Electricity-Coal-BEV	Coal	Electricity	Coal fired plant	CGH2 FCV
WtW-Electricity-Coal-w/CCS-BEV	Coal	Electricity	Coal fired plant (w/ CCS)	CGH2 FC HEV

Table 2.7: The crude oil based options under assessment

Chain	**Feedstock**	**Fuel**	**Process**	**Vehicle**
WtW-CG-Crude-Oil-ICEV	Crude oil	CG	Refining	ICEV
WtW-CG-Crude-Oil-IC HEV	Crude oil	CG	Refining	IC HEV

The key outputs for each STM listed above are: (i) the total energy consumption in the form of Mega Joules per kilometre (MJ/km), and (ii) the total GHG emissions in the form of grams of carbon dioxide equivalent per kilometre (gCO_2eq/km). Nevertheless, as noted earlier the STM is also run with end use (TtW) input data in the normalized form of per 1 MJ_W to generate output in the form of (MJ/MJ_W and gCO_2eq/MJ_W) for the comparison of performances across different sectors of energy resource use. This adds 6 chains for the electricity mains end use (light bulb, washing machine, among many others under consideration in the STM) such as the production, distribution, and use of NG-based electricity in a tungsten bulb.

2.4 The standardization process

The figure below presents the steps of the standardization process in a simple flow diagram. This is divided into two parts: the pre-statistical part and the statistical part as shown below.

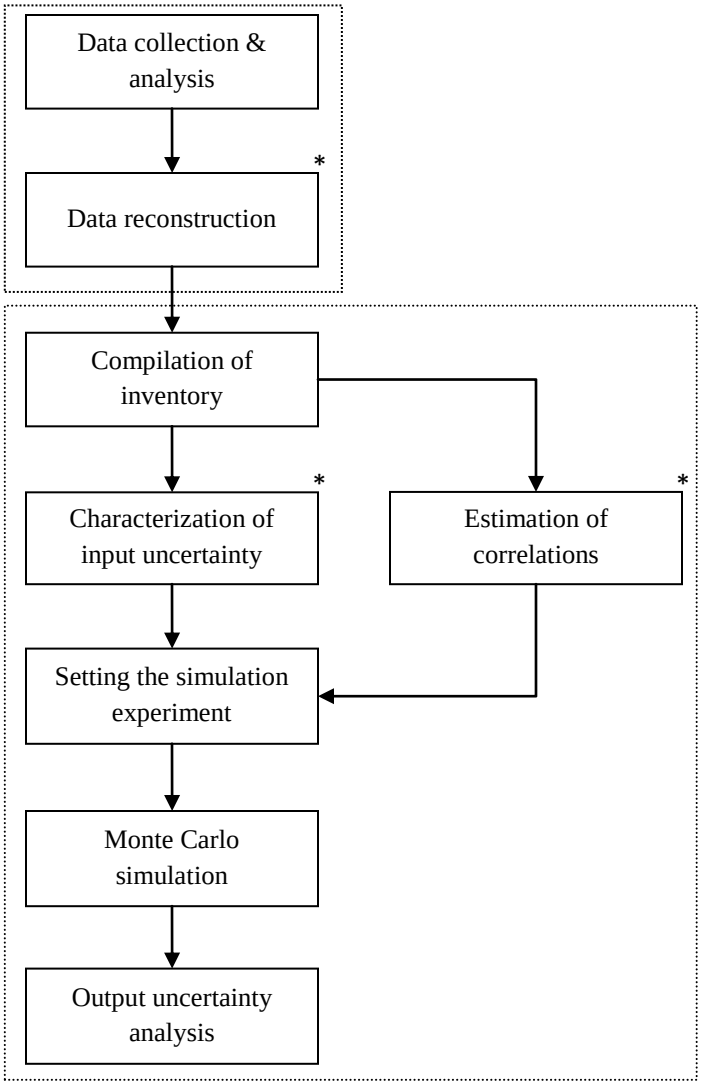


Figure 2.8: A simple flow diagram of the standardization process. The three steps marked with an asterisk (*) represent challenges that were addressed in the creation of the STM.

The first part of the process is the data analysis and reconstruction into a common form. This part is the pre-statistical part of the process and is concerned with the building up of the input samples[6] of the STM. The combination of the different system assumptions embodied within the

[6] The word 'sample' was used because sampling from all databases was undertaken.

reference models, where each system assumption is described by a set of modelling elements, builds uncertainty into the input as a superimposed effect of the differences in the modelling elements. The characterization of such uncertainty by a probability distribution is the first step in the statistical part of the process as shown in Figure 2.8. Having characterized the resulting uncertainty by probability distributions the Monte Carlo sampling technique was employed using the @Risk v5.7 simulation software (Palisade, 2010a) to propagate the inherent variability throughout the full chain of fuel production, distribution and use.

The standardization process involved three main challenges: (i) the data analysis and reconstruction, (ii) the characterization of the input uncertainty and (iii) the generation of realistic output modes from the simulation with due allowance for co-variance. This chapter is dedicated to thoroughly discussing the pre-statistics of the standardization process including in Section 2.4.4 a consideration of each database in turn. The next chapter (Chapter 3) is dedicated to the statistics of the standardization process which is primarily concerned with the characterization of the input distributions and the relationships between the variables of the STM.

2.4.1 The general components of a WtW model

A fuel consumption system such as the transport system is built up from a number of processes which produce, distribute and use the needed fuel (e.g. gasoline). Such processes can be grouped into a set of defined stages. For instance, the stages of the STM are shown in Figure 2.1.

2.4.1.1 Process structure

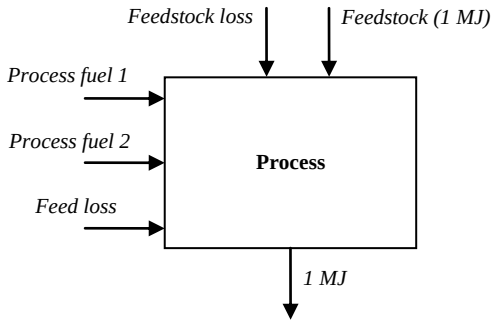


Figure 2.9: The energy components of a process

As presented in Figure 2.9 above the total energy consumed in a process is divided up into different categories. Assuming that the process in Figure 2.9 is the steam reforming of methane (SMR) the total energy consumption is a summation of the process fuels which include NG used as a process fuel, small amounts of electricity, and "feed loss" which is the amount of feedstock (i.e. NG) that is wasted in the reaction. The feed loss in an SMR depends on the yield of the total reaction including the water-gas shift reaction, i.e., in grams of H_2 per 1 gram of NG feedstock. In addition to the process fuels the total energy consumption for a process includes the "feedstock loss" due to a leakage in the process. Generally the energy losses under the category of feedstock loss relate to unusual leakages in the process such as spillage and boil-off (e.g. boil-off of liquid hydrogen). Nevertheless on a life cycle basis, the total energy consumption also includes the energy consumed upstream of the process fuels, i.e. the energy consumed to produce and distribute the amount of fuel (e.g. electricity) used in the process, such that:

$$TEC_P = \sum_{i=1}^{N} EC_{Fi}(1 + EC_{Fi^*}) + EC_{SL} \qquad \text{Eq. (2.1)}$$

where TEC_P is the total energy consumption for the process (P), N is the number of different process fuels, Fi refers to the type of the process fuel (e.g. EU electricity mix), EC_{Fi^*} is the upstream energy consumption for the supply of 1 MJ of the process fuel, EC_{Fi} is the amount of the process fuel consumption and EC_{SL} is the feedstock loss.

As seen in Figure 2.9 the main feedstock input to the process is equal to the output in its energy value. The energy use components of a process (as presented in Figure 2.9) are related to the GHG emissions by:

$$EM_{Fi} = EC_{Fi} \cdot EF_{Fi} \qquad \text{Eq. (2.2)}$$

where EM_{Fi} is the direct GHG emissions from the use of the process fuel i and EF_{Fi} is the emissions factor of that component. The emissions factor in Eq. (2.2) is a measure of the GHG emissions per 1 MJ of process fuel (e.g. NG) consumed in a specific unit of the process (e.g. steam boiler).

The GHG emissions of the whole process (TEM_P) is given by:

$$TEM_P = \sum_{i=1}^{N} EC_{Fi} \cdot EF_{Fi} + \sum_{i=1}^{N} EC_{Fi^*} \cdot EF_{Fi^*} + EM_P + EM_{SL} \qquad \text{Eq. (2.3)}$$

The GHG emissions for the whole process (TEM_P) also includes the emissions associated with the upstream processes of the supply of 1 MJ of process fuel (EM_{Fi^*}), the emissions from the process itself (EM_P), e.g. SMR, and any feedstock loss that has a global warming potential (EM_{SL}) such as the NG itself.

In the rest of this chapter the total vertical flow of energy into a process or a group of processes (i.e. a stage) per 1 MJ of output is denoted as x_i; on the other hand the corresponding total horizontal flow of energy per 1 MJ of output is denoted as y_i, where i is an integer for numbering purposes (i = 1, 2, 3...).

2.4.1.2 System structure

This section presents the general structure of a model which aggregates more than one process into a stage or more than one stage into a system. The following energy flow diagram represents the general structure of a system model composed from three stages.

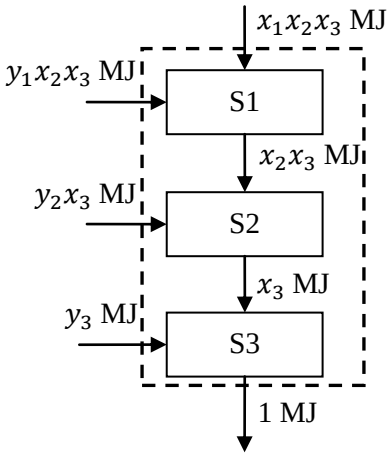


Figure 2.10: The general structure of a system model

In the same way the stages are aggregated into a system as shown in Figure 2.10 above, processes are aggregated into stages. For example the aggregation of the two processes (i) NG high pressure pipeline transport for 7000 km and (ii) the high/low pressure distribution of delivered NG to refuelling stations gives the NG transport stage. However, the figure above does not show the links of the process fuel energy (e.g. y_2x_3 MJ) to the upstream processes of

production and distribution whilst the energy consumption from such indirect processes is included in the account of the total energy consumption for the corresponding process or stage. In the case where the modelled system is a supply process to the same system a circular loop is created and that is solved by iterative calculation. For example, the system of diesel production and distribution is a supply process for the diesel used in the distribution of diesel in a tanker to the refuelling station (see Figure 2.11 below). Such circulars are common in the life cycle modelling of energy consumption systems.

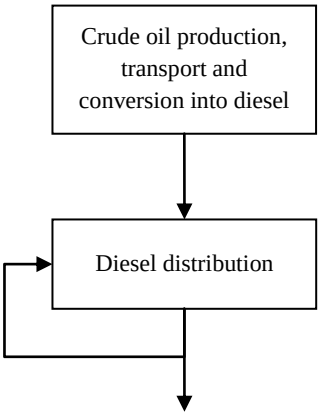


Figure 2.11: A representation of a circular loop

2.4.2 The structural differences between models

In the process of data analysis and restructuring models with varying levels of data transparency and different database structures were encountered. Such inconsistencies between the reference models make it extremely challenging to bring data in different models to a common form. The previous section described the general structure of a WtW model, however, it did not show the differences between the modelling structures of different reference models. The first step towards standardization was to understand the differences between the modelling structures of the reference models as without such understanding one cannot decompose and reconstruct data and that is the most crucial part of the standardization process.

As mentioned earlier one encounters different levels of data transparency between different models and without the complete access to the model database the understanding of the algorithm and the shaping of the modelling structure becomes problematic. However, with prolonged study and deep understanding of the databases made available for access through the public domain such as GREET v1.8c and the study of the trends in the data a deep understanding

of the differences in the structuring of the major WtW models was obtained and this is reflected, in part, in the identification of three different modelling structures presented in Figure 2.12 and described in the following sections as an example of the WtT system for hydrogen production from NG in a central SMR followed by distribution to the vehicle tank. The data for the assumed system is primarily adopted from the JEC model database with one assumption based on the GREET model database:

System processes	**Energy use per 1 MJ of output**
NG extraction & processing	*(l-1)* = 0.024 MJ (NG for mechanical energy supply plus unrecovered gas)
NG transport (7000 km)	*(i-1)* = 0.0092 MJ (feedstock loss: gas leakage) *j* = 0.0504 MJ (mechanical work)
NG distribution (500 km)	*(f-1)* = 0.00003 MJ (feedstock loss: gas leakage) *g* = 0.003 MJ (mechanical work)
SMR (central)	0.00 MJ[a] (feedstock loss) *(e-1)* = 0.315 MJ (NG process fuel including feed loss) *Note: The JEC model database assume no electricity use in the SMR whereas in the GREET model database a negligible amount of electricity (0.2% of the total direct energy loss) is assumed.*
Hydrogen distribution (including the compression of gaseous hydrogen)	*(a-1)* = 0.02 MJ (feedstock loss: gas leakage) *b* = 0.07 MJ of electricity (assumed in this example as NG based electricity from CCGT power plant)
Fuel upstream processes	**Energy use per 1 MJ of output**
NG fuelled Gas Turbine (GT) at source for the supply of mechanical work	*(k-1)* = 2.6 MJ of NG
NG fuelled Gas Turbine (GT) at destination for the supply of mechanical work	*(h-1)* = 2.33 MJ of NG
Combined Cycle Gas Turbine (CCGT) for the generation of electricity for hydrogen distribution	*(d-1)* = 0.818 MJ of NG
Electricity transport and distribution	*(c-1) = 0.017*

[a]Assumption from the GREET model v1.8c database (ANL, 2009)
Notes: The energy use assumptions are designated with small letters to build the algorithms of the different modelling structures as presented in Figure 2.12. The designations are listed in the table above according to their use in the algorithms in Figure 2.12 which follows the alphabetical order and keeps a track of the sequence of calculations.

Table 2.8: The data for the modelling of a hydrogen WtT system

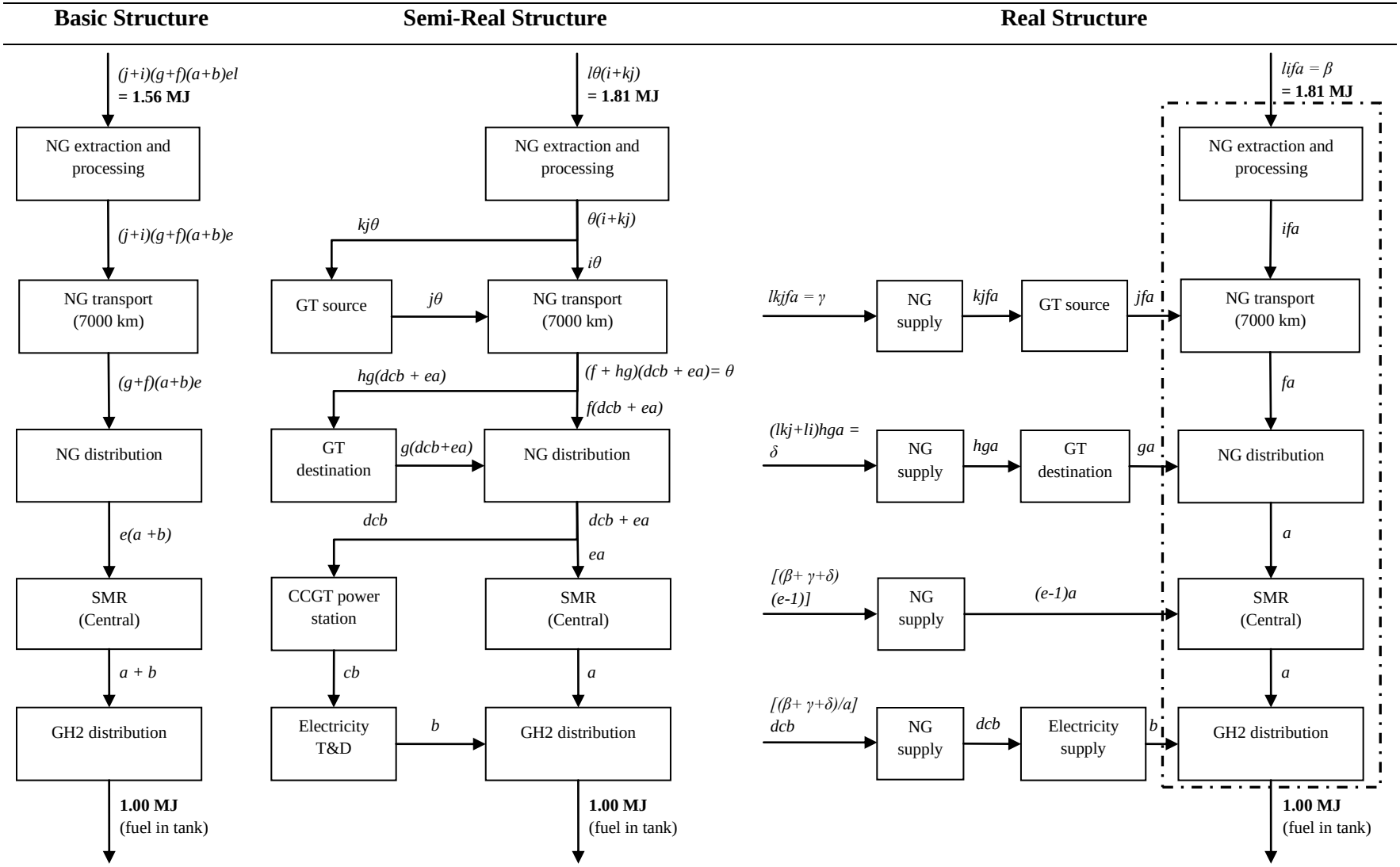


Figure 2.12: The different modelling structures of various WtW models

2.4.2.1 Basic structure

This structure was adopted by Bossel *et al.* (2003) in his eco-efficiency study model for various renewables based hydrogen options; also adopted by early models such as the fuel chain model of Arthur D. Little (ADL, 1996). In this type of system modelling there is no differentiation between the different energy uses across the chain as shown in Figure 2.12. All the energy input to the system always sum up at the upstream input to the chain (1.56 MJ as shown in Figure 2.12) and is calculated as follows:

$$TEI_S = \left(\frac{1}{e_{P1} \cdot e_{P2} \cdot \ldots \cdot e_{PN}}\right) \qquad \text{Eq. (2.4)}$$

where TEI_S is the total energy input to the modelled system per 1 MJ of output, N is the number of processes in the chain (N = 5 in the example shown in Figure 2.12) and e_{P1} is the standalone efficiency of the corresponding process (P1) such that:

$$e_{P1} = \left(\frac{1}{TEI_{P1}}\right) \qquad \text{Eq. (2.5)}$$

where TEI_{P1} is the sum of energy input to the corresponding process (P1) per 1 MJ of output. There is no evidence that the Bossel *et al.* (2003) study model accounts for the energy lost in the upstream processes of the process fuel supply for matters such as the mechanical work.

This basic structure of system modelling is simplistic and does not accurately represent reality. For instance, as shown in Figure 2.12 all the energy input for GH2 distribution is assumed as an output from the SMR plant and that is not realistic when the electricity used in the refuelling station for compression definitely does not come from an SMR plant.

2.4.2.2 Semi-real structure

This structure was adopted by the German L-B-Systemtechnik GmbH (LBST) company in the development of the calculation tool used for the GM-LBST study (GM *et al.*, 2002b) and the JEC study (Edwards *et al.*, 2007). As shown in Figure 2.12, in this type of system modelling there is a general track of the different energy uses across the chain such as the use of NG in the SMR and the other use of NG in a CCGT power plant to supply the compression electricity. Also the energy used upstream to supply the process fuels (i.e. mechanical work and electricity) is

taken into account. Thus the simplification in Eq. (2.4) for the calculation of the total energy input for the system does not apply.

However in this type of system modelling there is no differentiation between the system chain and the process fuel chain when the process fuel is based on the same primary resource. In such cases the process fuel chain merges with the system chain as shown in Figure 2.12 where all types of process fuels (NG, electricity and mechanical energy) stem from NG which is the primary resource for the modelled system. However in the case where any of the system fuels does not stem from the primary energy resource, the fuel supply chain does not merge with the system chain and thus the total energy consumption cannot sum up to the upstream input to the chain.

The implication of this model design is that the energy used in the running of the processes of fuel supply stem from the same primary resource as the main energy flow itself. For example in Figure 2.12 the energy use associated with the supply of the mechanical work for NG distribution is partially accounted under the account of the energy use for the NG production and transport processes. Further in the cases when the process fuel is the primary resource such as the NG fuel for the SMR plant as shown in Figure 2.12 the full account of the energy use in the processes of the fuel supply is accounted under the account of the energy use for the upstream processes of the system.

Although this modelling structure generally differentiates between the energy uses across the chain and is seen as adequately realistic, it does not further define the uses of the primary resource such that there is no differentiation between the use of NG as a process fuel and its use as a feedstock in the system. Interestingly in some chains this limitation generates non-realistic GHG emissions figures. For instance, in an electrolyzer for hydrogen production fuelled by coal-based electricity the direct GHG emissions is zero, however the life cycle GHG emissions is not zero because of the account of the indirect GHG emissions from the supply of the electricity lost in the process (i.e., feed loss). It is not realistic to say that the total GHG emissions of the hydrogen production stage is equal to zero while significant amount of coal-based electricity is used in the electrolyzer. The pitfall of the presented modelling structure as discussed in this example is that the total GHG emissions of the hydrogen production stage would be unrealistically zero because the electricity feed loss is not differentiated from the electricity

feedstock and thus the GHG emissions from the supply of lost electricity would be fully accounted for within the upstream processes of the system (i.e. within the electricity production and distribution and not, as it should be, under the account of the electrolysis process).

2.4.2.3 Real structure

This modelling structure was adopted by most of the reference models including the GREET and GEMIS models. The improvement in this algorithm on that presented in the previous section for the semi-real structure is that the energy use and thus the GHG emissions associated with the supply of the process fuels is completely accounted under the account of the corresponding process or the process of the system in which the fuel is consumed. What underpins this difference is the further differentiation between the energy uses across the chain where the algorithm of what is called the real structure differentiates the uses of the primary resource, i.e. NG in the presented example, between its use as a feedstock and otherwise its use as a process fuel such as the feed loss in the SMR and the NG used to heat up the process. Interestingly this differentiation splits the feedstock chain from the process fuels chains where the vertical flow as highlighted with the canvas in Figure 2.12 represents the flow of primary resource used as feedstock and does not include any process fuels. This model design ensures that each process or stage of the system is allocated its direct as well as the indirect consumption of energy. The same applies for the GHG emissions account.

2.4.3 The effect of variation in the modelling structure

As proven in Eq. (2.6) and shown in Table 2.9 below the variation in the modelling structure between the semi-real and the real structures affects the stage-wise data such as the energy consumption for the NG production stage but does not have an overall effect on the total measure for the whole system. The total increase of the energy consumption is matched with an equivalent total decrease and thus the overall effect of the presented change in the modelling structure on the total energy consumption for the system is nil. More closely the total increase in the energy consumption of the downstream processes (SMR and GH2 distribution processes) due to a change in the modelling structure from semi-real to real is matched with an equivalent total decrease in the energy consumption of the upstream processes (NG production, transport and distribution processes). The total energy consumption for the system remains at 0.81 MJ per 1 MJ of system output.

$$TEI_{SR} = l(i + kj)(f + hg)(dcb + ae)$$

and,

$$TEI_R = [lifa + lkjfa + (lkj + li)hga] + [lifa + lkjfa + (lkj + li)(e - 1)hga] + \frac{[lifa + lkjfa + (lkj + li)hgadcb]}{a}$$

$$= l(i + kj)fae + l(i + kj)hgae + l(i + kj)fdcb + l(i + kj)hgdcb$$
$$= l(i + kj)(fae + hgae + fdcb + hgdcb) = l(i + kj)(f + hg)(dcb + ae)$$

thus, $TEI_{SR} = TEI_R$

Eq. (2.6)

TEI_{SR} refers to the total energy input for the modelled system based on the semi real structure and TEI_R refers to the corresponding total energy input based on the real structure.

	NG production	NG transport	NG distribution	SMR	GH2 distribution	
	Energy use (MJ/MJ)	Energy use (MJ/MJ)	Energy use (MJ/MJ)	Energy use (MJ/MJ)	Energy use (MJ/MJ)	Total energy use (MJ/MJ)
Basic structure	0.037	0.086	0.004	0.343	0.090	0.560
Semi-real structure	0.042	0.283	0.144	0.321	0.020	0.811
Real structure	0.025	0.199	0.012	0.396	0.179	0.811
Standard deviation (σ)	**0.009**	**0.099**	**0.078**	**0.038**	**0.080**	**0.145**

Table 2.9: The different measures of energy consumption for the models presented in Figure 2.12

In contrast, as shown in Table 2.9 the change from a non-realistic structure (basic structure) to realistic structures such as the semi-real and real structures affects both the stage-wise data and the system data, i.e., the total energy consumption. The difference here is not just an improvement in the level of differentiation between the energy uses across the chain but a change from a non-valid structural assumption to a valid structural assumption.



Figure 2.13: A general representation of a system model based on (a) a realistic model on the left hand side, and (2) a simplified non-realistic model on the right hand side

The invalidity of the basic structure is now proved. Figure 2.13 gives a comparison and the resulting measures of the total energy input are not equivalent:

$$x_2(x_1 + y_1) + y_2 \neq (x_1 + y_1)(x_2 + y_2) \qquad \text{Eq. (2.7)}$$

Equality would only exist if $y_2 = y_2(x_1 + y_1)$, i.e. $x_1 + y_1 = 1$ but $x_1 > 1$. Thus under no circumstances is the simplied model mathematically valid. Physically it is not realistic because it does not differentiate between different fuels and furthermore assumed that all of the process fuels are fed into the beginning of the chain.

The important question now is: What are the implications of the variation in the modelling structure on the output of the standardization model (STM)? As seen in Table 2.9 the variation in the modelling structure is a common source of variability between the processes of the modelled system. However, the variation in the modelling structure between the semi-real and real structures has no effect on the total result. Thus the variation in the modelling structure when confined between the mentioned structures generates co-variance between the variables of the STM but should not affect the model output. This co-variance contributes to the relationships between the input variables of the STM which as will be elaborated in Chapter 3 are described by correlation coefficients. Now nearly all the modelling structures encountered in the input samples of the various STMs are either of the two forementioned structures and in an ideal simulation, where the relationships between the input variables of the model are accurately described, the variability embedded in the input samples due to the variation in the modelling structure would not propagate to the output.

2.4.4 The database structure and data transparency

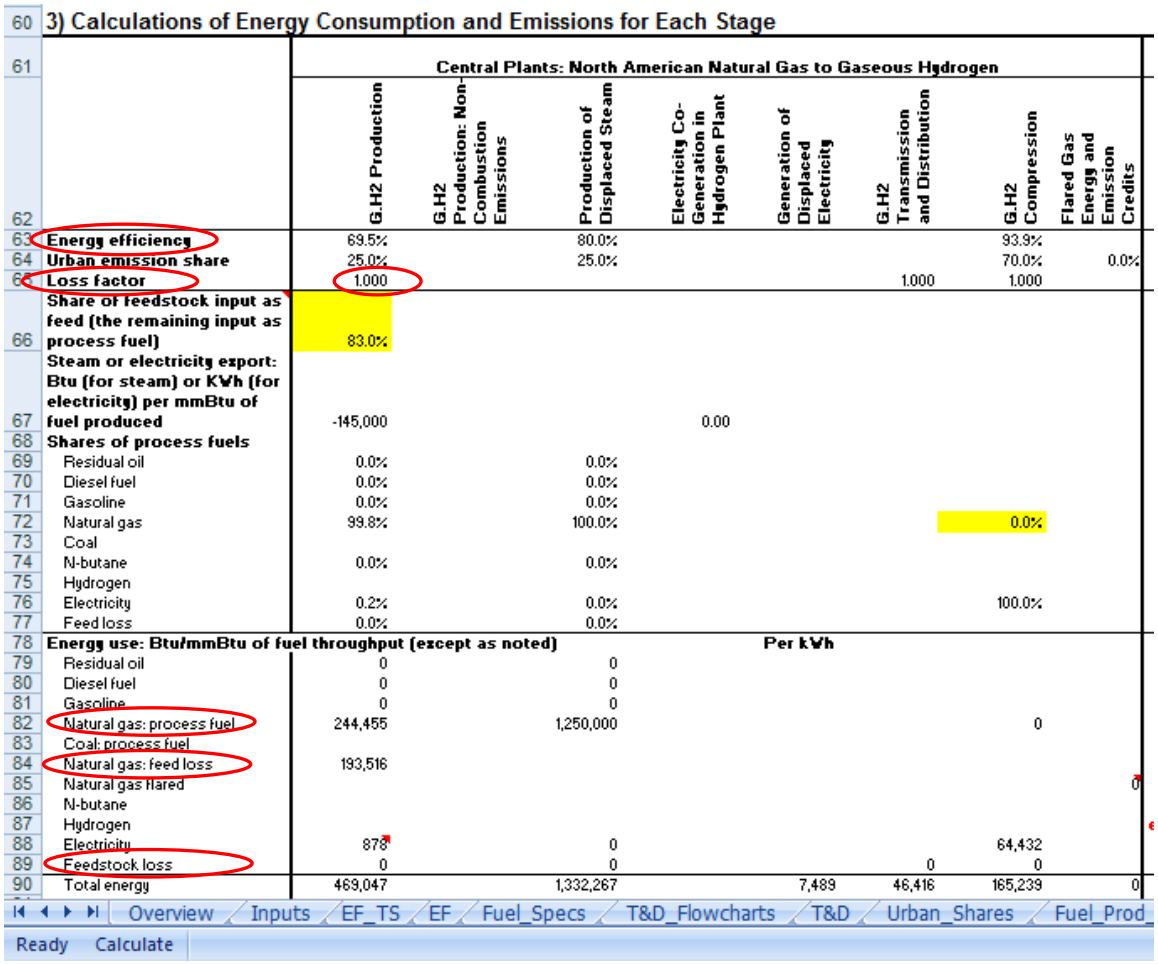
Five databases, and how they were used, are now presented.

2.4.4.1 GREET model

The GREET model (ANL, 2009) provides the highest level of data transparency among the reference models considered in the STM. Since the release of Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model version 1.5 in 1998, Argonne National Laboratory has expanded, updated, and upgraded the model. The newly released version of the GREET model (version 1.8c) that is used in the STM provides complete access to the model software which includes a multidimensional spreadsheet that consists of 27 Microsoft® Excel sheets. This includes the *Input* sheet through which one can change the default values of some input parameters and rerun the model.

In simply using the GREET model to analyse the energy consumption and GHG emissions for different transport systems the model provides a front end user interface (GREETGUI) which links to the model spreadsheet running in the background and a general understanding of the input parameters is adequate to run the model. However, the standardization process involves data restructuring that requires a deep understanding of each model sheet and the algorithms embedded for the calculations. The spreadsheet of the model is built from thousands of parameter values; it took much time and meticulous work throughout the course of this study to overcome the complexities of the model spreadsheet and develop a complete understanding of the parameter values in the spreadsheet and the embedded algorithms to manipulate data and workout the input assumptions for the STM. The references that provided support in the process of developing an understanding of the model spreadsheet include, but are not limited to, Wang *et al.* (2005) and Wang (1999).

The GREET model calculates energy use and emissions for each individual stage (e.g. crude oil recovery) by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc. As shown in Figure 2.14 the energy use is expressed in the form of Btu of energy consumed per MMBtu of energy throughput. And as shown in Figure 2.15 the GHGs considered in the model include CO_2, CH_4, N_2O, CO and VOC and the emissions are expressed in grams per MMBtu of energy throughput.



3) Calculations of Energy Consumption and Emissions for Each Stage

Central Plants: North American Natural Gas to Gaseous Hydrogen

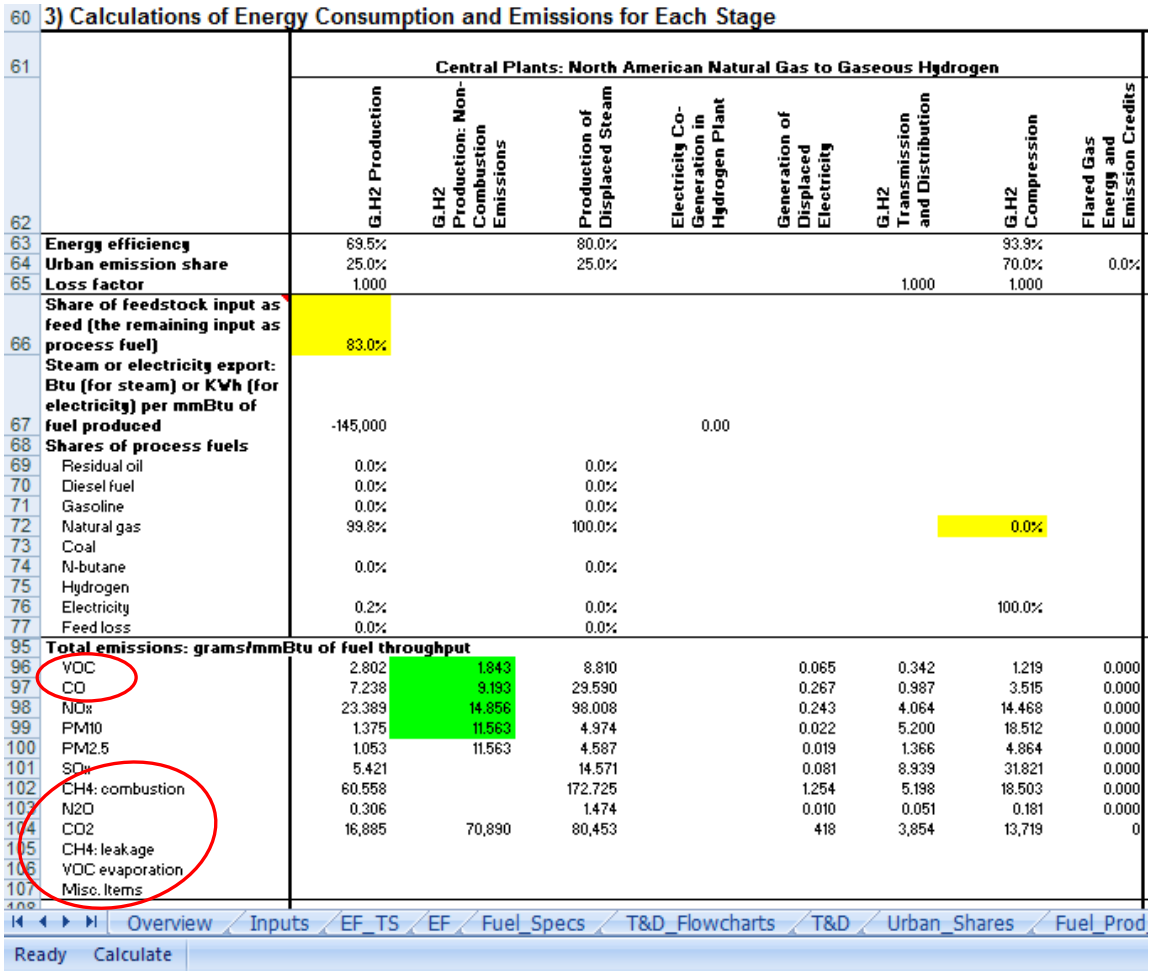
	G.H2 Production	G.H2 Production: Non-Combustion Emissions	Production of Displaced Steam	Electricity Co-Generation in Hydrogen Plant	Generation of Displaced Electricity	G.H2 Transmission and Distribution	G.H2 Compression	Flared Gas Energy and Emission Credits
Energy efficiency	69.5%		80.0%				93.9%	
Urban emission share	25.0%		25.0%				70.0%	0.0%
Loss factor	1.000					1.000	1.000	
Share of feedstock input as feed (the remaining input as process fuel)	83.0%							
Steam or electricity export: Btu (for steam) or KWh (for electricity) per mmBtu of fuel produced	-145,000			0.00				
Shares of process fuels								
Residual oil	0.0%		0.0%					
Diesel fuel	0.0%		0.0%					
Gasoline	0.0%		0.0%					
Natural gas	99.8%		100.0%				0.0%	
Coal								
N-butane	0.0%		0.0%					
Hydrogen								
Electricity	0.2%		0.0%				100.0%	
Feed loss	0.0%		0.0%					
Energy use: Btu/mmBtu of fuel throughput (except as noted)					**Per kWh**			
Residual oil	0		0					
Diesel fuel	0		0					
Gasoline	0		0					
Natural gas: process fuel	244,455		1,250,000				0	
Coal: process fuel								
Natural gas: feed loss	193,516							
Natural gas flared								0
N-butane								
Hydrogen								
Electricity	878		0				64,432	
Feedstock loss	0		0			0	0	
Total energy	469,047		1,332,267		7,489	46,416	165,239	0

Overview | Inputs | EF_TS | EF | Fuel_Specs | T&D_Flowcharts | T&D | Urban_Shares | Fuel_Prod

Ready Calculate

Figure 2.14: A snapshot from the GREET model spreadsheet showing the energy consumption for each stage in the production and distribution of gaseous hydrogen

A sample of the most important pieces of data in the model spreadsheet is depicted in Figure 2.14 and Figure 2.15. The standardization model does not have interest in this aggregated form of data although GREET generates this form at three levels: (i) feedstock stage, (ii) fuel stage and (iii) WtW. However, the aggregation algorithms of various chains were studied to understand the modelling structure and know how so as to reconstruct data for various processes in the desired form. The STM aims for the most differentiated form of data which allows for the manipulation and workout of data to the desired form.



3) Calculations of Energy Consumption and Emissions for Each Stage

Central Plants: North American Natural Gas to Gaseous Hydrogen

	G.H2 Production	G.H2 Production: Non-Combustion Emissions	Production of Displaced Steam	Electricity Co-Generation in Hydrogen Plant	Generation of Displaced Electricity	G.H2 Transmission and Distribution	G.H2 Compression	Flared Gas Energy and Emission Credits
Energy efficiency	69.5%		80.0%				93.9%	
Urban emission share	25.0%		25.0%				70.0%	0.0%
Loss factor	1.000					1.000	1.000	
Share of feedstock input as feed (the remaining input as process fuel)	83.0%							
Steam or electricity export: Btu (for steam) or KWh (for electricity) per mmBtu of fuel produced	-145,000			0.00				
Shares of process fuels								
Residual oil	0.0%		0.0%					
Diesel fuel	0.0%		0.0%					
Gasoline	0.0%		0.0%					
Natural gas	99.8%		100.0%				0.0%	
Coal								
N-butane	0.0%		0.0%					
Hydrogen								
Electricity	0.2%		0.0%				100.0%	
Feed loss	0.0%		0.0%					
Total emissions: grams/mmBtu of fuel throughput								
VOC	2.802	1.843	8.810		0.065	0.342	1.219	0.000
CO	7.238	9.193	29.590		0.267	0.987	3.515	0.000
NOx	23.389	14.856	98.008		0.243	4.064	14.468	0.000
PM10	1.375	11.563	4.974		0.022	5.200	18.512	0.000
PM2.5	1.053	11.563	4.587		0.019	1.366	4.864	0.000
SOx	5.421		14.571		0.081	8.939	31.821	0.000
CH4: combustion	60.558		172.725		1.254	5.198	18.503	0.000
N2O	0.306		1.474		0.010	0.051	0.181	0.000
CO2	16,885	70,890	80,453		418	3,854	13,719	0
CH4: leakage								
VOC evaporation								
Misc. Items								

Overview | Inputs | EF_TS | EF | Fuel_Specs | T&D_Flowcharts | T&D | Urban_Shares | Fuel_Prod

Ready Calculate

Figure 2.15: A snapshot from the GREET model spreadsheet showing the emissions for each stage in the production and distribution of gaseous hydrogen

As seen in Figure 2.14 and Figure 2.15 the database provides detailed data on each process of the chain and breaks down the energy uses and emissions. Moreover, further details can be extracted by studying the algorithms that underpin the process data and by probing the constituent assumptions and by changing the parameter values including critical input parameters. The algorithms span across the relevant sheets and cells in the model and this helps one to keep track of the different parameters and assumptions that make up the process data.

Given the richness of the data in the GREET model spreadsheet one can collect the required data from across the model sheets and calculate the energy consumption and GHG emissions in the desired form. For elaboration purposes the author assumes the sub-chain for which data was posted in Figure 2.14 and Figure 2.15 for the central production and distribution of hydrogen and works out the data in the form that suits the STM structure.

The data posted in Figure 2.14 and Figure 2.15 was for the sub-chain concerning the central production and distribution of hydrogen from NG. The processes by which it is elaborated to get it into the desired form for the STM are now explained. The following table summarizes the data that is required to calculate the energy consumption and GHG emissions in the desired form for the assumed sub-system.

Data	**Description**
Total energy use for the SMR plant with the design specified in the input sheet	That is the total energy use including the total upstream energy use for the supply of the process fuels
Amount of steam/electricity exported	When the plant design is chosen as non-default with electricity or steam export the amount of the steam or electricity produced at the plant gate is required
Total energy use for the production of steam/electricity by the displaced system	In calculating the credit from the export of steam or electricity the energy used by the displaced system to produce a certain amount of steam or electricity is required
In the case of electricity exported, efficiency of electricity T&D (transport and distribution)	In the case of electricity export we require the efficiency of T&D to calculate the amount of electricity at the user site
Feedstock loss in the GH2 production	As shown earlier this is important in modelling a system for the calculation of the feedstock input to the process in the chain
Total energy use for the GH2 T&D	That is the energy used to transport and distribute gaseous hydrogen to the refuelling station
Total energy use for GH2 compression	GREET considers the refuelling station as a separate stage from distribution
Emissions of GHGs which are CO_2, CH_4, CO, VOC and N_2O of each process	Required to measure the total GHG emissions for each process
Conversion factors for CO and VOC to CO_2 and the Global Warming Potentials (GWPs) of different GHGs	To calculate the GWP of CO and VOC we first convert them to CO_2, i.e., to CO_2 equivalent emissions

Table 2.10: The description of the data required to model the assumed sub-system and construct data in the desired form

The example deduced from Figure 2.14 and Figure 2.15 assumes a plant design with steam export of 145,000 Btu (A). The assumed plant does not integrate Carbon Capture and Sequestration (CCS) technology. The plant design was set through the input sheet (not seen in the snapshot figures) before the model was run. The model was re-run with other assumptions which include electricity export and CCS technology. The energy consumption of the SMR plant is given as a whole as can be seen in Figure 2.14 and that is 469,047 Btu; this includes the total energy use for the supply of process fuels which are listed as NG (99.8%) and electricity (0.2%) but does not include the energy credit from the export of steam. The energy efficiency which is circled with red in Figure 2.14 does not include the indirect energy uses and/or credit and represents the energy conversion efficiency of the system.

The steam exported replaces steam produced by the displaced system which is not identified in the GREET database. However, the important parameter is the energy used by the displaced system to produce one unit of steam and that is given as shown in Figure 2.14 as 1,332,267 Btu per MMBtu (B) of steam throughput. Therefore in the GREET model database the energy use does not always refer to the energy lost but sometimes refers to the energy input. In the case of steam export steam output from the displaced system is being replaced and this is equivalent to replacing the energy input required to produce the replaced steam. The amount of replaced steam is equal to the amount of steam exported and that was quoted from the database in the above paragraph; thus the energy credit is equal to the energy input replaced:

$$Energy\ credit = \frac{A \cdot B}{10^6}$$

The subtraction of the energy credit from the total energy use of the SMR production process as quoted above and presented in Figure 2.14 will result in the total energy consumption in the form of Btu per MMBtu. The simple conversion of the result to the form of MJ/MJ using the relevant energy unit conversion factor finishes the construction of the energy consumption for one stage of the STM and that is the fuel production (FP) stage.

On the other hand, the database provides the total energy use (including the total energy use for the process fuels supply) for both the GH2 T&D and the GH2 compression processes as 46,416 and 165,239 Btu per MMBtu, respectively. The STM fuel distribution (FD) as defined earlier includes all the processes between the outlet of the production site and the vehicle tank, thus the total energy use of the GH2 T&D and compression (which is the major process in the refuelling station) processes should be combined into one stage. This is done according to the GREET modelling structure and requires knowing the feedstock loss for the subsequent processes in the chain, i.e. the GH2 compression in the given example. This parameter is very important in the GREET model to aggregate data as desired. The feedstock loss for the GH2 compression process is given in the list of different energy uses as shown in Figure 2.14. The zero feedstock loss implies that the feedstock input to the process is equal to the energy throughput (1 MMBtu).

The GREET model is a multidimensional spreadsheet and is not graphical thus the modelling structure of the GREET model in Figure 2.12 (real structure) was shaped after a prolonged and deep study of the algorithms in the model spreadsheet and is not obvious. To avoid confusion

between the algorithm used in the model spreadsheet for the aggregation of data and the modelling structure as presented earlier in this chapter the aggregation of the GH2 T&D and compression processes will be performed based on both the algorithm in the model spreadsheet and the structure as shaped in Figure 2.12 and it will be proved that the mentioned graphical structure accurately describes the algorithm in the model spreadsheet. It should be noted that the graphical representation of the GREET model algorithm is first shaped and compared to other structures for WtW modelling in the current study.

According to the model spreadsheet the total energy use per 1 MMBtu from the GH2 distribution stage which combines the GH2 T&D (process 1) and compression (process 2) processes is calculated as follows:

$$TEU_1 \cdot k_2 + TEU_2 \qquad \text{Eq. (2.8)}$$

where TEU refers to the total energy use per 1 MMBtu throughput from the corresponding process and k refers to what is known in the GREET model as the loss factor. This is presented in Figure 2.14 and Figure 2.15 and circled with red. The loss factor is actually the total feedstock input to the process per 1 Btu of fuel throughput. Thus k represents the energy contained in the process output plus the feedstock lost in the process. The general equation developed by GREET to account for the feedstock loss effects is (Wang, 1999, p.27):

$$TEU_i = \sum_{i}^{J} EU_i \times k_{i+1} \times k_{i+2} \times \ldots \times k_J \qquad \text{Eq. (2.9)}$$

where i is the ith process of the chain and J is the number of the last process in the chain. The equation was adjusted to match the notations used in here. The total energy used in a process is multiplied by the loss factors of all the downstream processes. The multiplication of the process total energy use with the loss factors of the downstream processes as depicted in Eq. (2.9) translates into accounting for the effect of the feedstock losses.

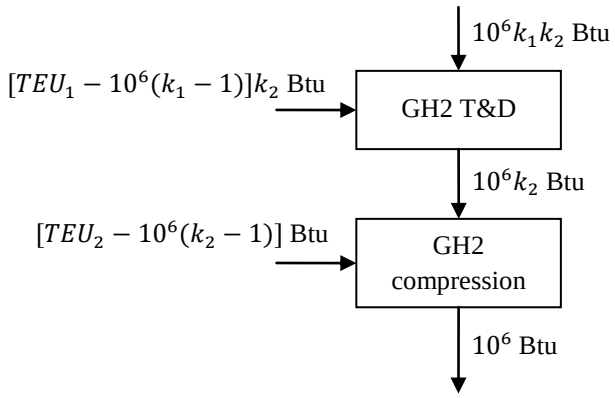


Figure 2.16: The graphical representation of the algorithm for the aggregation of the GH2 T&D and compression processes based on the deduced modelling structure of the GREET model as presented in Figure 2.12

Figure 2.12 accurately describes the algorithm in the model spreadsheet and relates to the origin of Eq. (2.9). As mentioned earlier the total energy use in the model spreadsheet include all process fuels with the upstream energy uses plus the feedstock loss, if any. However, in the graphical model the feedstock loss is part of the vertical flow of the feedstock energy and that is split from the horizontal flow of the process fuels. Thus the feedstock loss per 1 Btu of fuel throughput, which based on the definition of k is $(k-1)$, is subtracted from the total energy consumption per 1 Btu of fuel throughput (which is equal to the TEU as given in the model spreadsheet per 1 MMBtu of fuel throughput divided by 1 million) of the corresponding chain to give the total horizontal energy input to the process per 1 Btu of fuel throughput. The aggregation of the two processes in the given example results in the model presented in Figure 2.16 above. Now the total energy use for the system, GH2 fuel distribution (FD) according to the STM, per 1 MMBtu of fuel throughput is the total energy input minus the total energy output such that:

$TEU_{FD} = 10^6 k_1 k_2 + [TEU_1 - 10^6(k_1 - 1)]k_2 + [TEU_2 - 10^6(k_2 - 1)] - 10^6$ $= 10^6 k_1 k_2 + k_2 TEU_1 - 10^6 k_2(k_1 - 1) + TEU_2 - 10^6 k_2 + 10^6 - 10^6$ $= \cancel{10^6 k_1 k_2} + k_2 TEU_1 - \cancel{10^6 k_1 k_2} + \cancel{10^6 k_2} + TEU_2 - \cancel{10^6 k_2}$ $= k_2 TEU_1 + TEU_2$ $= Eq.(2.8)$	Eq. (2.10)

The above equation proves that the deduced modeling structure of the GREET model accurately describes the algorithm in the model spreadsheet. The graphical shaping of the GREET model algorithms and its comparison with other models has not been done previously. The loss factor of the GH2 compression stage is given as shown in Figure 2.14 as 1.000 and that means that the feedstock loss is equal to zero and thus the total energy use for the GH2 distribution stage per 1

MMBtu of fuel throughput is simply the summation of the total energy use of the constituent processes as given in the model spreadsheet. Now after simple unit conversions from Btu/MMBtu to MJ/MJ the output is the GH2 fuel distribution (FD) stage in the size and form desired by the STM.

Now, as shown in Figure 2.15, the emissions are separately given for various types of emissions. The first step in the reworking of the emissions data is to generate a total GHG emissions measure for each process in the model spreadsheet. This includes GHG emissions from both the combustion of process fuels and non-combustion processes such as chemical reactions, fuel leakage and fuel evaporation. In fact the CO and VOC are criteria pollutants, not GHGs, but GREET considers their indirect effects in the atmosphere and assume they convert to CO_2. The residence time of VOC and CO in the atmosphere is short (less than 10 days), thus the carbon contained in VOC and CO is converted into CO_2 emissions in GREET. Although not directly given as seen in Figure 2.15, GREET assumes a carbon ratio by weight for VOC and CO of 0.85 and 0.43, respectively, and converts to CO_2 emissions as shown in Eq. (2.11).

$$EM_{CO2} = \frac{44 \cdot (EM_{CO} \cdot 0.43 + EM_{VOC} \cdot 0.85)}{12} \qquad \text{Eq. (2.11)}$$

In addition to the CO_2 emissions from VOC and CO emissions, the GHG emissions account includes direct emissions of CO_2, CH_4 and N_2O. These three GHGs are combined with their Global Warming Potentials (GWPs) to estimate the CO_2-equivalent GHG emissions. The GWPs are ratios of potential warming effects of other gases relative to CO_2. The well known Kyoto Agreement, signed by major industrial countries in 1997 to set the GHG emissions reduction goals for individual countries, adopted the IPCC-recommended GWPs for the 100 year time horizon. These are listed for the three major GHG gases in Table 2.11 below. So, default GWPs in GREET are those estimated by IPCC for the 100 year time horizon and are used in the data work for the standardization model to estimate the total GHG emissions.

	Time horizon		
Gas	**20 years**	**100 years**	**500 years**
CO_2	1	1	1
CH_4	56	21	6.5
N_2O	280	310	170

Table 2.11: The GWPs of Greenhouse Gases. Source: (IPCC, 1996)

The gases of interest are circled in Figure 2.15 with red. The VOC and CO emissions as described above are converted to CO_2 emissions and the total emissions of each of the three major GHGs is multiplied by the corresponding GWP as quoted in Table 2.11 to estimate the total GHG emissions of the relevant process. The miscellaneous emissions usually include emissions credit from the recovery of boiled off liquid gas and CO_2 emissions credit from the burning of biomass (e.g. bagasse). Given the total GHG emissions of each process in the model spreadsheet the calculation of the GHG emissions credit from the export of steam or electricity and the aggregation of processes into stages follows the same procedure as explained for energy use but in this case by weight of GHG emissions per 1 MMBtu and not by amount of energy per 1 MMBtu of fuel throughput.

Generally, the data for each process in GREET that is required for the STM is individually and meticulously studied, manipulated and worked out according to the modelling structure of the model. Some of the exceptions include (i) the neglect of the upstream energy use and GHG emissions of the feed loss for the biomass conversion processes such as fermentation, (ii) the use of the term "energy use" to represent the energy input rather than the energy loss in some cases and (iii) the presentation of the feedstock loss for the electricity T&D process in the form of a percentage. The feedstock lost in the electricity T&D was taken as 8%, the default value in GREET. This was converted to energy use per MMBtu and a loss factor was calculated in the STM workbook (Appendix C1).

2.4.4.2 GM-LBST and JEC models

As mentioned earlier the models for these two studies were both built by the LBST in Germany and have the same modelling structure. This is the semi-real structure of Figure 2.12. The GM-LBST study provides no access to the model software however reports input and output data in many forms in the full background report (GM *et al.*, 2002a) including technical data about the processes of the various systems under study. The same applies to the JEC study which provides no access to the model software but details the input data (only of expended energy) for all pathways in 5 Excel workbooks (JRC *et al.*, 2008a) and the output data in WTT Appendix 2 (JRC *et al.*, 2008b).

Generally speaking data is categorized into three types: (i) input data, (ii) pre-output data and (iii) output data. The elements of the input samples of the STM cannot be raw input data such as

the auxiliary fuel use and feedstock loss of a specific process. The size of the input variables only allows for the standardization if it can fit processes of different type and design and under different assumptions, choices and boundaries. For instance, where an electricity production process is CCGT, another option may be SCGT (single cycle gas turbine); and where electricity is an auxiliary fuel for a specific SMR process it may not be an auxiliary fuel for another SMR process; and where steam is exported in one conversion process it may not be exported in another conversion process and so on. In fact the standardization model combines various pathways of the same chain and does not describe one specific pathway.

The second larger form of sample elements that can fit processes of different type, design, etc is the pre-output data such as the total energy consumption of an individual process on a life cycle basis (including the upstream energy use) per unit of energy throughput. However, the structure of the GM-LBST model as presented in Figure 2.12 does not model individual processes but models the whole system in one piece. There is a clear distinction between the modelling approaches of the GREET model and the GM-LBST and JEC models. GREET models individual processes and aggregates the individual processes into one system; however, the algorithm developed by LBST models the whole system in one piece and cannot generate data in the pre-output form such as energy consumption on a life cycle basis per unit of energy throughput for an individual process. As shown earlier in this chapter by the semi-real modelling structure the accounting of the upstream energy uses may involve the merging of the process fuel chain with the system chain. Thus the pre-output form of the STM sample elements does not allow for the standardization of data from varying modelling structures. However, the STM sample elements in the output form such as the energy consumption on a life cycle basis per unit of energy throughput from the system (MJ/MJ_{fuel}) does allow for the combining of data for different process types and designs, under different assumptions, choices and boundaries, and from models of different modelling structure. However, this form of data elements adds one source of correlation between the input variables of the STM and that is the variation of the modelling structure.

Another implication of the modelling structure of the GM-LBST and JEC models on the database structure is seen in the input data where the process feedstock use is not differentiated into (i) main feedstock, (ii) process fuel and (iii) feedstock loss. It was mentioned earlier that a

semi-real modelling structure does not differentiate between the uses of the feedstock and this reflects on the database structure as seen in Figure 2.17 below.

	Unit	Input BE (LB-UB)	Output BE (LB-UB)
Natural gas	MJ/MJ_{H2}	1.417 (1.346-1.488)	-
Hydrogen	MJ	-	1.000
Heat	MJ		0.150
CO_2	g/MJ_{H2}	-	288 (273-302) [1)]
CH_4	g/MJ_{H2}	-	0.057

[1)] „CO_2-content" of natural gas: 203 g/kWh of NG

95							
96	GPCH2/3	**Hydrogen production via steam reforming (central)**					
97			I/O	Unit	Amount		Comment
98		NG	Input	MJ/MJ_{H2}	1.3150		
99		Hydrogen	Output	MJ	1.0000		>3 MPa
100							

Figure 2.17: The input data of a large hydrogen steam reforming (SMR) plant from the GM-LBST full background report (GM *et al.*, 2002a) and the Excel sheets of the JEC model (JRC *et al.*, 2008a)

The natural gas use as seen in Figure 2.17 is 0.417 MJ (best estimate) or 0.315 MJ per 1 MJ of hydrogen throughput and is not differentiated. Unlike the GREET model database which as shown in Figure 2.14 clearly differentiates between the different uses of the process feedstock and that is required to calculate the loss factor and aggregate the individual processes into one system.

		Standard step	Energy expended (MJx/MJf)				Net GHG emitted (g CO_2eq/MJf)			CO_2	CH4	N_2O
			Total primary			Fossil						
			Best est.	min	Max		Best est.	min	Max	g/MJ	g/MJ	g/MJ
GMCH1	**NG EU-mix, 1000 km, on-site reforming**											
	NG Extraction & Processing	1	0.04	0.02	0.07		4.9			1.7	0.1	0.0
	NG Transport	3	0.03	0.01	0.03		2.8			1.6	0.0	0.0
	NG Distribution	3	0.01				0.9			0.8	0.0	0.0
	On-site reforming	4	0.52	0.49	0.55		86.6			85.8	0.0	0.0
	Compression	5	0.24	0.22	0.26		10.0			9.3	0.0	0.0
	Total pathway		**0.84**	0.81	0.89	**0.83**	**105.2**	103.3	108.0	99.3	0.23	0.001
GPCH1a	**Piped NG, 7000 km, on-site reforming**											
	NG Extraction & Processing	1	0.04	0.02	0.09		5.7			2.0	0.15	0.000
	NG Transport	3	0.29	0.10	0.32		22.1			15.0	0.28	0.001
	NG Distribution	3	0.01				0.8			0.8	0.00	0.000
	On-site reforming	4	0.52	0.49	0.55		84.7			83.9	0.03	0.000
	Compression	5	0.24	0.22	0.26		10.0			9.3	0.02	0.000
	Total pathway		**1.11**	0.94	1.18	**1.09**	**123.2**	113.5	127.7	111.0	0.48	0.001
GPCH1b	**Piped NG, 4000 km, on-site reforming**											
	NG Extraction & Processing	1	0.04	0.02	0.08		5.2			1.8	0.13	0.000
	NG Transport	3	0.14	0.05	0.15		11.0			7.1	0.16	0.000
	NG Distribution	3	0.01				0.8			0.8	0.00	0.000
	On-site reforming	4	0.52	0.49	0.55		84.7			83.9	0.03	0.000
	Compression	5	0.24	0.22	0.26		10.0			9.3	0.02	0.000
	Total pathway		**0.95**	0.86	1.00	**0.94**	**111.7**	106.7	114.7	102.9	0.34	0.001
GPCH2a	**Piped NG, 7000 km, central reforming, pipeline**											
	NG Extraction & Processing	1	0.04	0.02	0.08		5.2			1.8	0.13	0.000
	NG Transport	3	0.26	0.09	0.29		20.1			13.7	0.25	0.001
	NG Distribution (HP)	3	0.01				0.8			0.7	0.00	0.000
	Central reforming	4	0.32	0.29	0.34		74.1			73.7	0.02	0.000
	Gaseous Hyd distribution & comp.	5	0.22	0.21	0.24		9.1			8.5	0.02	0.000
	Total pathway		**0.86**	0.71	0.93	**0.85**	**109.3**	100.9	113.6	98.4	0.42	0.001
GPCH2b	**Piped NG, 4000 km, central reforming, pipeline**											
	NG Extraction & Processing	1	0.04	0.02	0.07		4.7			1.6	0.12	0.000
	NG Transport	3	0.12	0.04	0.14		10.1			6.4	0.14	0.000
	NG Distribution (HP)	3	0.01				0.8			0.7	0.00	0.000
	Central reforming	4	0.32	0.29	0.34		74.1			73.7	0.02	0.000
	Gaseous Hyd distribution & comp.	5	0.22	0.21	0.24		9.1			8.5	0.02	0.000
	Total pathway		**0.72**	0.63	0.76	**0.71**	**98.8**	94.0	101.3	91.0	0.30	0.001

Figure 2.18: A snapshot from the JEC data appendices showing the most relevant form of data provided by the LBST tool based models (JRC *et al.*, 2008b)

The type of data from the JEC model database shown in Figure 2.18 is the most relevant for the STM. The flexibility provided by the form of the STM sample elements and the factorized form of the output data as reported by the JEC and GM-LBST models makes data reconstruction straightforward. The data for the different processes of the system as reported in Figure 2.18 can be aggregated into the STM building blocks by simple summation, where applicable, such as the summation of the NG transport and the NG distribution energy losses into NG transport (feedstock transport stage of the STM) energy loss.

Assumptions:

Assumption 1:

The drawback of these models is the lack of availability of the model software in the public domain. Occasionally one wants to change some processes in a given system and remodel with a new component. For example where the system of hydrogen fuel from a central electrolyser fuelled with wind (offshore) electricity is considered, one might want to consider liquid hydrogen distribution and/or the onsite production versions of this system. Given the limited

accessibility in such cases one builds up other versions of the system using stage-wise output data from other models. In looking at the algorithms of the semi-real modelling structure in Figure 2.12 it can be seen that the profile of the upstream processes is dependent on the profile of the downstream processes in a chain, but the opposite is not true. Thus in building up a chain from pieces of output data that stem from different modelled systems the assumption is that the feedstock use downstream of a process in the approximated system is similar to that in the source system model. For instance, in exchanging the central electrolysis and hydrogen distribution and compression processes with onsite electrolysis and hydrogen compression (without distribution) processes, it is assumed that the downstream feedstock use of the upstream processes (i.e. electricity production and distribution) do not change significantly. This is reasonable; parameters for central and onsite electrolyzers are very similar and the hydrogen distribution processes generally do not consume feedstock apart from the losses which are negligible.

Assumption 2:

The efficiency is the universal metric of energy performance and therefore, as seen in Figure 2.19 below, the STM input data sheets include a measure of the in-chain efficiency of each process of the system. The efficiency is calculated by:

$$e_{P1} = \frac{1}{(1 + EC_{P1})} \qquad \text{Eq. (2.12)}^{7}$$

The value is a rough approximation of the actual efficiency because the output of the processes in a chain are not necessarily equal to 1; the output of a process in an LBST tool based model is not restricted to the feedstock losses downstream but includes feedstock used as a process fuel and overall that may total far more than 1. For instance, in the example presented in Figure 2.12 the output from the NG production process is $\theta(i+kj)$ = 1.77 MJ to deliver both the NG losses downstream in the chain and the use of NG as a process fuel in the SMR plant.

[7] The e_{P1} refers to the in-chain efficiency where previously in describing the basic modelling structure it was used to represent the standalone efficiency of the process. That is because in the case of databases which model individual processes on a life cycle basis, the in-chain efficiency is equal to the out-of-chain or standalone efficiency. However, in the case of the LBST tool based databases which do not model individual processes on a life cycle basis there is no out-of-chain efficiency and the process efficiency on a life cycle basis is only applicable in chain. EC_{P1} is the energy consumed in the process.

84	CGH2 from NG (Central)				
85		Energy input	Energy use	Efficiency	GHG emissions
86		MJ/MJ	MJ/MJ		gCO2eq
87	**Piped NG, 7000 km, central reforming, pipeline:**				
88	NG extraction & processing	1.04	0.04	0.962	5.20
89	Transport (pipeline, 7000 km)	1.30	0.26	0.794	20.10
90	NG distribution/HP	1.31	0.01	0.990	0.80
91	Central reforming	1.63	0.32	0.758	74.10
92	GH2 distribution & compression	1.85	0.22	0.820	9.10
93	Total =	*1.85*	*0.85*	*0.541*	
94					
95	**Feedstock Production**		**0.04**	0.962	**5.20**
96	**Feedstock Transport**		**0.27**	0.787	**20.90**
97	**Fuel Production**		**0.32**	0.758	**74.10**
98	**Fuel Distribution**		**0.22**	0.820	**9.10**

Figure 2.19: A snapshot from the STM input data sheets showing data that stem from the JEC database

Moreover, it is noted that for the data from the JEC and GM-LBST models the STM input data sheets include a measure of the cumulative energy input including the energy delivered to the vehicle. The same was done by Lopez *et al.* (2009) as presented in Figure 2.20. This only reflects the scale of increase in the energy use as we move downstream through the chain and does not reflect the actual increase in the energy input to the system.

	Energy input[a,b] MJ/MJ_{diesel}	Energy losses[b] MJ/MJ_{diesel}	Greenhouse gases(GHG)[b] g/MJ_{diesel}
Crude oil extraction	1.027	0.027	3.6
Crude oil transport	1.039	0.012	0.9
Refining	1.099	0.060	4.7
Distribution	1.119	0.020	1.1
Total	1.119	0.119	10.2

[a] Cumulative, includes the energy delivered to the vehicle.
[b] Per MJ delivered to the vehicle.

Figure 2.20: A snapshot from Lopez *et al.* (2009) showing the GM-LBST data for diesel supply used in the cited study for the life cycle analysis of refuse trucks in the city of Madrid

2.4.4.3 GEMIS model

As mentioned earlier the GEMIS model (GEMIS, 2008) adopts the real modelling structure as described in Section 2.4.2.3. Although the model provides unrestricted access to the model software and the embedded data the user can only see the interface but not the algorithms that underpin the calculations. However, the model makes a clear distinction between what is known in GEMIS as the process chain (which is the feedstock chain) and the fuel cycle (which is the process fuel supply chain) and that is evident in Figure 2.21 below where the mechanical energy fuel cycle is different from the pipeline transport process chain and the splitting of the two types

of chains from each other is the most important feature of the real modelling structure as presented earlier in Figure 2.12.

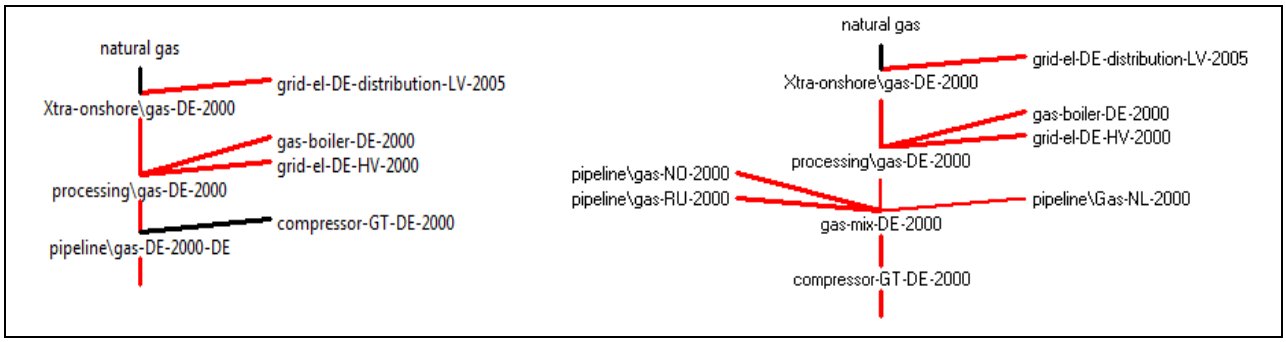


Figure 2.21: (a) On the left hand side shows a NG pipeline transport process chain from GEMIS, and (b) on the right hand side shows the mechanical energy fuel cycle (Öko-Institut, 2008)

Nevertheless, unlike the GREET model this type of model is not designed to generate stage-wise output data. The output data from the GEMIS model can only be generated on an aggregated level, i.e., on a cumulative process (involves one or more single processes) basis and not on a single process basis. Thus the author is confronted with the challenge of decomposing cumulative processes to single processes. As an example, the gasoline from crude oil WtT chain is taken. In GEMIS such a chain can be computed at different *cumulative* stages:

1. Oil-crude-mix-DE-2010 (P1*)
2. Pipeline\oil-crude-DE-mix-2010 (P2*)
3. Refinery\gasoline-DE-2010 (P3*)
4. Filling-station\gasoline-DE-2010 (P4*)

Each of the processes listed above stems from the crude oil well and therefore the energy consumption and the emissions of GHGs, for instance, were computed "up to" the refinery stage per 1 MJ of refinery output but not "for" the refinery stage per 1 MJ of WtT output. Whilst decomposition of computed processes to single processes of size and form that fit the building blocks of the STM can be made as shown below, not all the stages that result from such decomposition directly fit the building blocks of the STM. Further decomposition was sometimes required to derive the desired output.

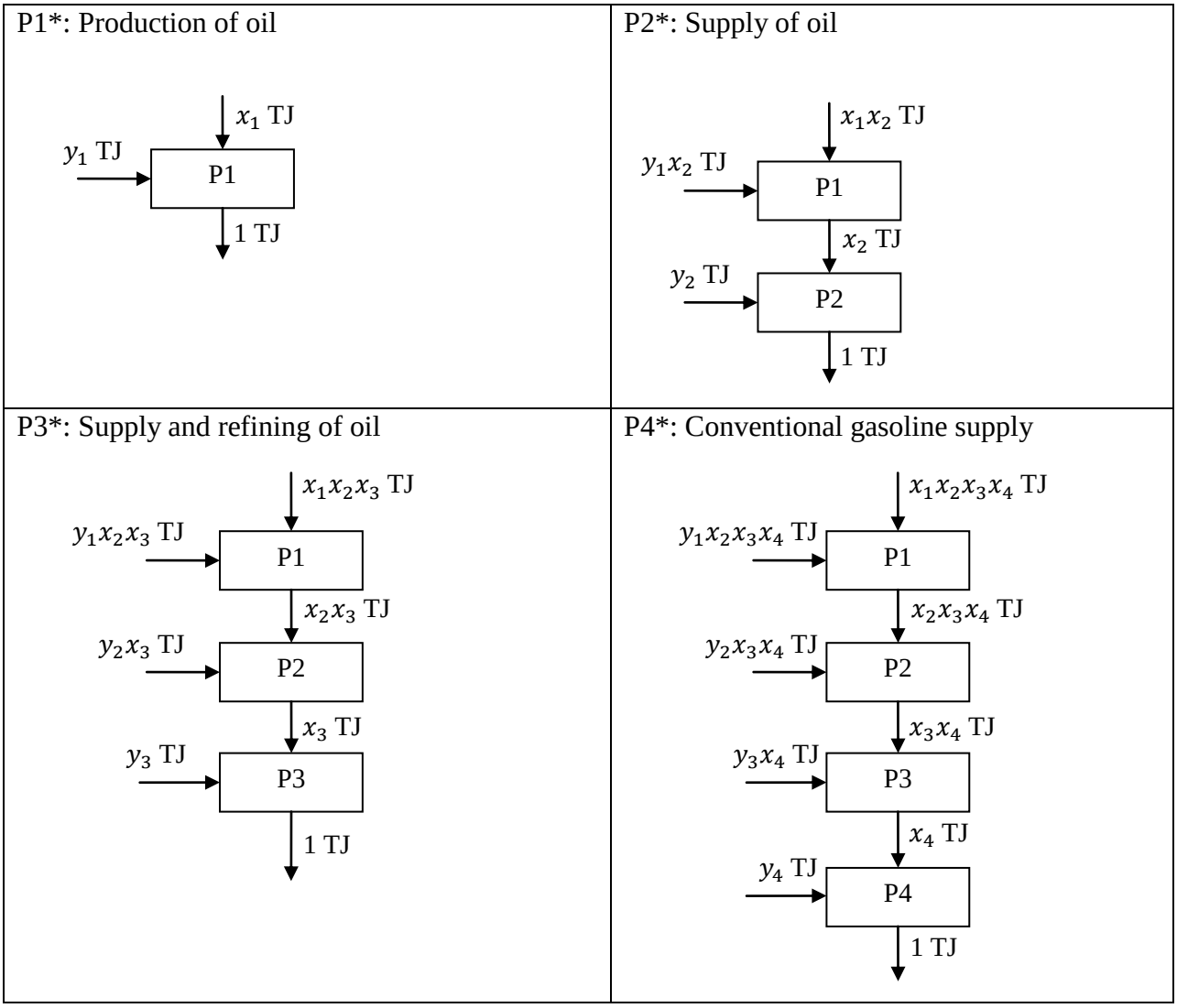


Figure 2.22: The modelling of the cumulative processes of a conventional gasoline WtT chain as predefined by GEMIS

Given the modelling structure of the GEMIS model the cumulative processes were modelled as shown in Figure 2.22 above. Although through GEMIS one can build up any cumulative process from more than 3000 processes embedded in the model, one can only compute the energy consumption and GHG emissions for the cumulative processes and not directly for the constituent processes. Each of the flows in Figure 2.22 above represent a cumulative process, first for the production of crude oil, second for the supply of crude oil to the refinery, third for the supply and refining of crude oil, and fourth for the supply of conventional gasoline to the vehicle tank or the WtT chain.

GEMIS does not compute the energy consumption and GHG emissions of, for example, the refining process per 1 MJ of WtT output. Instead GEMIS calculates energy consumption in Tera

Joules (TJ) and GHG emissions in $kgCO_2$ equivalent. The author makes justified assumptions to allow the calculation of the energy consumption and GHG emissions for single processes per 1 TJ of WtT output, such that the actual energy consumption of, for example, the refinery process is:

$EC_{P3} = x_3x_4 + y_3x_4 - x_4$ $= x_4(x_3 + y_3 - 1)$	Eq. (2.13)

And the assumed energy consumption of the same process is calculated from the processes given in Figure 2.22:

$EC_{P3} = EC_{P3^*} - EC_{P2^*}$ $= (x_1x_2x_3 + y_1x_2x_3 + y_2x_3 + y_3 - 1) - (x_1x_2 + y_1x_2 + y_2 - 1)$ $= x_3(x_1x_2 + y_1x_2 + y_2) + y_3 \cancel{- 1} - (x_1x_2 + y_1x_2 + y_2) \cancel{+ 1}$ $= (x_1x_2 + y_1x_2 + y_2)(x_3 - 1) + y_3$	Eq. (2.14)

If x_1, x_2, x_3, and x_4 = 1, then Eq.(2.13) and Eq. (2.14) are equal.

Now that in the real modelling structure x represents energy used as main feedstock and therefore is nearly equal to 1 because the feedstock loss for most of the processes is close to or equal to zero. Such losses are largest for the T&D of liquid fuels in vessels and transmission of gaseous fuels via pipelines which are subject to fuel evaporation and/or leaks, yet they are still relatively negligible. For instance, as shown in Table 2.8 the feedstock loss for the distribution of NG over a distance of 500 km is 0.00003 MJ and that is nearly zero. In the worst case the feedstock loss may not exceed 0.0092 MJ and that is the transport of NG over a very long distance of 7000 km via high pressure pipeline. As such the assumptions made in the decomposition of GEMIS data to the desired size are completely justified and result in negligible error.

As mentioned earlier further decomposition is required in some cases to derive the desired output. For instance, in GEMIS the road transport of biomass feedstock does not form a

cumulative stage (process) by itself. For instance, the sugarbeet fermentation process can be computed as two cumulative stages compromising:

1. Farming\sugarbeet-DE-2010 (P1*)
2. Fermentation\bio-EtOH-big(sugarbeet)-DE-2010 (P2*)

Here the road transport of biomass feedstock is embodied in the biofuel production stage. So if the cumulative process is treated as above one obtains the energy consumption and the emissions of GHGs of the following two single processes:

P1: Sugarbeet production
P2: Sugarbeet transport + EtOH (ethanol) production

The latter single process (P2) does not fit the STM wherein the biomass feedstock production and the biomass feedstock transport stages are combined into the biomass feedstock supply stage. Thus P2 was further decomposed to fit the feedstock supply stage of the STM. GEMIS allows the editing of a pre-defined process; a new cumulative process similar to P2* can be created with transport distance equal to zero (P2.1*). Now by modelling the two cumulative processes (P2* and P2.1*) as shown in the previous example, the energy consumption and the emissions of GHGs of three single processes can be calculated:

P1: Sugarbeet production
P2.1: Sugarbeet transport
P2.2: Ethanol production

where,

$$EC_{P2.1} = EC_{P2^*} - EC_{P2.1^*} \qquad \text{Eq. (2.15)}$$

and,

$$EC_{P2.2} = EC_{P2} - EC_{P2.1} \qquad \text{Eq. (2.16)}$$

This is an example of where the structure of an output stage does not directly fit the building blocks of the STM. Via further decomposition, the database of GEMIS was used to create hundreds of cumulative processes so as to build up and compute the various WtT pathways of the chains under study by the STM.

2.4.4.4 LEM model

The LEM (Delucchi, 2003) is similar to the life cycle parts of GREET, but LEM is broader in scope: it covers more countries, wider time frames (up to 2050), more transport modes (light duty passenger cars, full size buses, etc), more aspects of the life cycle (such as materials), more pollutants and more relevant effects (such as price effects). Nevertheless, this does not mean that the LEM is a richer source of information for the STM. The STM is of determined scope focussed on transport by light duty passenger cars, the associated GHG emissions and energy consumption. Thus what makes a model a good reference for the STM is the comprehensiveness of the pathways under study and the construction of the output results, and not the broadness of its scope. The LEM does not consider much variability of the process type, size and design, transport and distribution scenarios, and feedstock type. For instance, the biomass feedstock for ethanol production is restricted to corn and grass. It can be seen that the focus of the LEM was to expand the scope across many countries, time frames, transport modes, life cycle aspects, pollutants and effects, rather than to expand the scenarios of the present study.

Moreover, on the structural level the LEM output aggregates the gas leaks and flares for the whole system such that it includes leakages from all stages, including losses at dispensing station and from pipelines, without factorization. Also, the definition of the life cycle stages of the LEM are different than the definition of the STM stages. For instance, for hydrogen from electrolysis "fuel production" according to LEM is the entire cycle of electricity resource from production to electrolysis whereas such a cycle is divided into three stages in the STM: feedstock production which represents the electricity production, feedstock transport which represents the electricity transmission and fuel production which represents the electrolysis process. (STM defines the feedstock for electrolysis as electricity while LEM defines the same as water).

As such the LEM did not form a major source of WtT information for the STM, but formed a complete reference for the TtW information which includes the energy use and GHG emissions of the light duty vehicles (such as the gasoline ICEV and CGH2 FCV). The WtT output data used in the STM was retrieved from one of the serious of reports on the LEM available on the author's faculty web page (Delucchi, 2005). The main report for the full documentation of the LEM is Delucchi (2003). Except for the WtT output data for the sugar based ethanol chains

which was retrieved from the Canadian version of the LEM, GHGenius version 3.15 ((S&T)^2 Consultants Inc., 2009).

It is also noted that the LEM documentation forms one of the best references for the methodological aspects of the life cycle assessment of energy and emissions. Most of the documentation provided for the LEM (Delucchi, 2003) is dedicated for the demonstration of how precisely fuel cycle energy and emissions should be calculated. In fact the mathematical structure of GREET as described earlier was based on an early version of the LEM (Delucchi, 1997) which demonstrates how to calculate fuel cycle energy and emissions with the account for the effects of fuel loss. One of the distinctive arguments of Delucchi on the methods of fuel cycle assessment in terms of emissions is the account of the indirect effects of gases in the atmosphere in estimating the GWPs. In calculating the total CO_2-equivalent emissions, the LEM uses CO_2-equivalency factors (CEFs) that convert mass emissions of all of the non-CO_2 gases into the mass amount of CO_2 with an equivalent effect on global climate. The CEFs are similar to but not necessarily the same as the GWPs of the Intergovernmental Panel on Climate Change (IPCC) as discussed earlier. The differences between the IPCC GWPs and the LEM CEFs are not discussed further in this thesis. Further details on the CEFs are in Appendix D of Delucchi (2003).

2.4.4.5 Ulf Bossel eco-efficiency model

The Ulf Bossel model adopts the basic structure of WtW modelling. Thus the data is simply reported in the form of stage efficiency as shown in Figure 2.23 below.

	Energy cost in HHV of H_2	Factor	Path A gas	Path B liquid	Path C onsite	Path D hydride
Production of H_2						
Electrolysis	43%	1.43	1.43	1.43		1.22*
Onsite production	65%	1.65			1.65	
Packaging						
Compression 20 MPa	8%	1.08	1.08			
Liquefaction	40%	1.40		1.40		
Chemical hydrides	60%	1.60				1.60
Distribution						
Road, 20 MPa H_2, 100 km	6%	1.06	1.06			
Road, liquid H_2, 100 km	1%	1.01		1.01		
Storage						
Liquid H_2, 10 days	guess: 5%	1.05		1.05		
Transfer						
10 MPa to 40 MPa	3%	1.03	1.03		1.03	
Delivered to User						
Energy Input/HHV of H_2			1.69	2.12	1.69	1.95**

* Only 50% of the hydrogen released comes from electrolysis
** Excluding energy needed to produce alkali metals

Figure 2.23: Energy consumption for different hydrogen pathways (Bossel *et al.*, 2003)

The energy input to the system is calculated as depicted in Eq. (2.4) and the energy input to the downstream stages in the chain is calculated as follows:

$$TEI_{P1(S1)} = TEI_{S1}$$
$$TEI_{P2(S1)} = TEI_{S1} \cdot e_{P1}$$
$$TEI_{P3(S1)} = TEI_{S1} \cdot e_{P1} \cdot e_{P2}$$

Eq. (2.17)

and the energy consumption of the processes is simply the difference between the input and the output such as:

$$EC_{P1(S1)} = TEI_{P1(S1)} - TEI_{P2(S1)} \qquad \text{Eq. (2.18)}$$

Although Bossel *et al.* (2003) is not comprehensive and focuses on the hydrogen paths from renewable energy, it is included in the STM to represent a considered but non-conventional point of view on the future of the hydrogen economy.

2.4.4.6 The TtW data elements

2.4.4.6.1 Vehicle operation

The data for the vehicle operation was directly sampled from GM-LBST (GM *et al.*, 2002a), JEC (JRC *et al.*, 2008c), GREET (ANL, 2009), MIT (Weiss *et al.*, 2000) and LEM (Delucchi, 2003) models mainly in the standard form of unit energy or unit mass per kilometre (e.g. gCO_2eq/km). As emphasized earlier in this chapter this form of data does not allow for the generation of results in the normalized form of unit energy or unit mass per unit work done (e.g. gCO_2eq/MJ_W) which is required for the supplementary comparison of different options across the two major sectors of energy resource use, i.e., the transport and power sectors. Thus besides the sampling of vehicle performance data from the reference models in the standard form for the generation of output in the same form for the comparison of different transport options, the data elements were converted to the normalized form for cross-section comparison.

Interestingly, it was found that the data for the efficiency and GHG emissions of the vehicle is reported in the majority of the reference models only in the form of MPG (miles per gallon) and unit mass of CO_2 equivalent emissions per kilometre (or mile), respectively. This does not allow for the normalization of the data elements which requires the efficiency of the vehicle in the form of both percentage (%) and miles per gallon.

Efficiency → MJ_W/MJ_{fuel}

MPG → miles per gallon → km per gallon → km/MJ_{fuel}

Now, (km/MJ_{fuel})/efficiency → $(km/MJ_{fuel})/(MJ_W/MJ_{fuel})$ → km/MJ_W

Thus, $km/MJ_W * gCO_2eq/km = gCO_2eq/MJ_W$

Therefore without the vehicle total efficiency in its universal form, i.e. in the form of percentage (%), besides the MPG the conversion of the data elements to the normalized form is not possible. This requirement confined the references for the vehicle performance to the GM European study given that the GM-LBST annex (GM *et al.*, 2002a) is the only database which fulfils the pre-requisite of reporting data of the total vehicle efficiency in both the percentage (%) and MPG

forms. Given the total vehicle efficiency in the form of percentage (%) the calculation of the energy consumption in the form of MJ_{fuel}/MJ_W is straight forward:

1/efficiency = fuel input

In fact the energy consumption in a vehicle is equal to the fuel input as there is no output of energy that can be used to do work. As shown in Figure 2.24 below all the mechanical energy generated from the fuel combustion is consumed in the movement stage and there is no energy output from the complete operation of the vehicle.

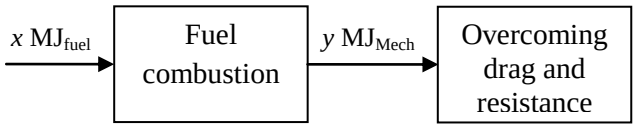


Figure 2.24: A simple energy flow diagram of the vehicle operation. Note there is no energy output.

Nevertheless, the assumption for the efficiency of a Battery Electric Vehicle (BEV) in the analysis of output in the form of MJ_{fuel}/MJ_W is adopted from Ahman (2000). A last point: the output of the STM in the normalized form is less complete than that in the standard form because the size of the input sample at the TtW stage is much smaller (confined to the relevant assumption from the GM-LBST database and the assumption from Ahman in the case of a BEV). That is because of the limitation of data transparency for vehicles operation across different models.

2.4.4.6.2 Electric powertrain

The efficiency of the end use powertrain for the non-transport chains under study was adopted from two main sources. The efficiency data for a series of residential-commercial electric powertrains such as electric appliances, space heating, among many others was adopted from a published study on the evaluation of energy utilization efficiency in the Turkish residential-commercial sector by Utlu and Hepbasli (2003). Also efficiency data on the use of electricity in the industrial sector was adopted from a review on the analysis and evaluation of energy utilization efficiency of countries by Utlu and Hepbasli (2007). The distribution in Figure 2.25 below represents the distribution of the energy consumption of the electricity mains use under different types of electric powertrains.

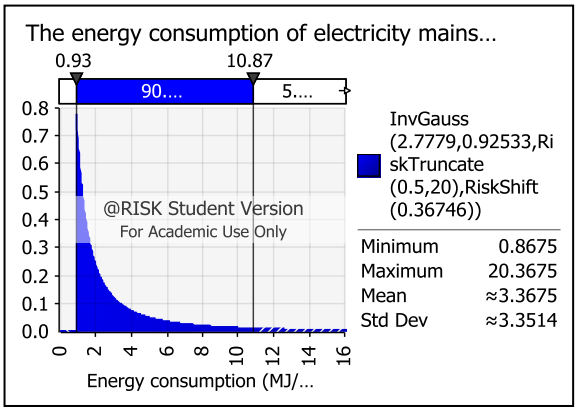


Figure 2.25: The energy consumption distribution of electricity mains use. Note: the y-axes of all the distributions presented in this thesis represent probability density.

On the other hand, the GHG emissions from the electric powertrains and battery electric vehicles is well known to be zero marking them extremely high on the environmental performance scale.

2.5 Limitations

As mentioned earlier, for the reasons given when discussing Table 2.1, vehicle life cycle is not considered. It is also noted that although cost is not originally a subject of LCA, the analysis of this dimension becomes necessary when planning the implementation of potential technologies. Therefore the results which follow in Chapter 5 should not be taken as indicative of commercial viability.

3 Statistical Methods

3.1 What is a model?

In cases where processes in the real world are far too complicated to understand it is a good idea to strip the processes of some of their features, to leave us with models of the original processes (Morgan, 1999). In other words a model is an approximation of a real process and in many cases it is given a mathematical formulation. In cases where a model is given a mathematical formulation simulation is quite often a useful tool for investigating how the behaviour of the model may change following a change in the model parameters.

3.2 Types of WtW results

In Chapter 1 the difference between the type of results generated by the STM and that of the results generated by classic WtW models were described in general terms. In this section we will compare them in statistical terms. The word "complete" is often used in the current work to describe the nature of the result that is generated by the STM. It is important that one understands the intended meaning of completeness. The ultimate goal of the STM is to create a robust probabilistic measure by generating all the possibilities under discussion. Thus the space of interest is the totality of all possible outcomes under discussion (an example of a measure under discussion is the WtT energy loss of the production and distribution of CNG fuel from NG). Now the larger the sample space, the more complete is the result which implies that the standardization process is a continuous process and does not end at the level achieved in the current project. Later in this chapter it is shown that the space of interest for the standardization model is hypothetical.

3.2.1 Sample space

The assessment and presentation of the effects of uncertainty through the simulation of mathematically formulated models is actually a study of functions of the form:

$$\mathbf{y} = \mathbf{f}(\mathbf{x}) \qquad \text{Eq. (3.1)}$$

where the function **f** represents the models under study, $\mathbf{x} = [x_1, x_2, \dots, x_J]$ is a vector of model inputs and **y** is a vector of model predictions. The goal of uncertainty analysis is to determine the uncertainty in the elements of **y** that results from the uncertainty in the elements of **x**. In the case

of WTW modelling the function **f** and hence **y** is real valued and therefore the representation in Eq. (3.1) becomes:

$$y = f(\mathbf{x}) \qquad \text{Eq. (3.2)}$$

where y is a real variable of model predictions.

The uncertainty in the elements of **x** is assumed to be characterized by a sequence of probability density functions:

$$f(x_1), f(x_2), f(x_3), \dots, f(x_J) \qquad \text{Eq. (3.3)}$$

where $f(x_J)$ is the distribution associated with the element x_J and J is the number of elements contained in **x**. The distributions in Eq. (3.3) are assumed to characterize a degree of belief with respect to where the appropriate values of the elements of **x** are located for use in the evaluation of function f (Helton and Davis, 2002).

Finally the distributions in Eq. (3.3) and any relationships imposed on the elements of **x** (i.e., function f in Eq. 3.2) define what is known in the terminology of probability theory as the sample space. In other words, the sample space is made from all possible coordinates:

$$[(x_1, x_2, \dots, x_J), y] \qquad \text{Eq. (3.4)}$$

This space represents all the possibilities (values of y) in the particular universe "under consideration". Here it is important not to confuse y (set of model predictions) with the distribution for y which can be presented as a probability density function (PDF) or as a cumulative distribution function (CDF). If a CDF is used to provide a complete representation of the uncertainty in y it can be formally defined by the integral:

$$P(Y_a \leq y \leq Y_b) = \int_{Y_a}^{Y_b} f_y[f(\mathbf{x})].d[f(\mathbf{x})] = 1 \qquad \text{Eq. (3.5)}$$

where the interval of y in the sample space is $\{I_y: Y_a \leq y \leq Y_b\}$, f_y is the probability density function for y and f is the model function. Further, again for clarification, the interval of y is defined by all the values that it can take in the space under consideration and the area under f_y is the cumulative probability that y lies within I_y which is definitely equal to 1 because f_y is a non-negative density function:

(1) $f_y(y) \geq 0$ Eq. (3.6)

(2) $\int_{Y_a}^{Y_b} f_y(y).dy = 1$ Eq. (3.7)

Eq. (3.6) and Eq. (3.7) above define the terms of a density function. Here it is worth noting that although the input to the model is a vector, the distribution of the output predictions is not a joint density function of the form:

$f_{y_1,y_2,\ldots}(y_1, y_2, \ldots) \geq 0$ Eq. (3.8)

because as mentioned earlier in the case of WTW modelling the function **f** and hence **y** (see Eq. 3.1) is real-valued.

However, the mathematical evaluation of the integral in Eq. (3.5) is not amenable and a method for approximation must be used. Here lies the importance of simulation which can be used to approximate the distribution of y in the sample space. Later in this chapter the discussion will be on the different techniques of simulation and the accuracy in approximating the distribution of y.

3.2.2 The stability of a random measure

When the distributions in Eq. (3.3) are continuous the sample space is countably infinite simply because the size of the random sample that can be generated from a continuous distribution is infinite. As such the sample space is made from an infinite number of coordinates as described in Eq. (3.4) where each coordinate represents a point in space. Through simulation we can generate large numbers of points in space and approximate the sample space to certain proximity. The accuracy to which the sample space is approximated determines the stability of the output distribution with respect to the totality of all outcomes under consideration by the model. This has to do with the number of iterations under which the simulation is run and the efficiency of the simulation method (please refer to Section 3.3.4 for more details). The question that counts most is: What is the stability of the output distribution with respect to the totality of all outcomes under discussion? The answer to this question relates to the completeness of the result. The more complete the representation of the space of interest, the more stable is the output distribution; the space of interest is the universe under discussion rather than the particular universe considered by the model. The former space represents the goal of the model and that is to achieve a result

which is as absolutely complete as possible (assuming that the space of interest is real and not unlimited).

As described earlier, the sample space derives from the elements of the input vector through the evaluation of the model function. This implies that the observation of the result's completeness is best done from the input of the model. To show how the size of the input population is directly related to the size of the sample space and thus to the completeness of the result, an experiment with a known full population was undertaken. Three models were set up each with a certain percentage of the full population as the input population. The system chosen was the WtT production and distribution of conventional gasoline from crude oil and the output measure under study is the total emissions of GHGs.

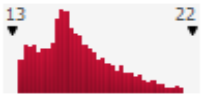
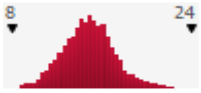
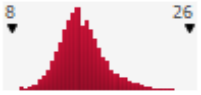
Model Name	Population	Graph	Min	Mean	Max
WTT-CG-Crude-Oil-EM-P1	25%		13.7001	16.3438	21.3277
WTT-CG-Crude-Oil-EM-P2	50%		9.2948	15.0437	22.1512
WTT-CG-Crude-Oil-EM-P3	100 %		9.5624	15.3238	24.0596

Table 3.1: The results of the simulation output with varying percentage of the full population as an input to the model

The data set of each model is shown in Appendix A and the percentage of the full population is approximate. The curve in Figure 3.1 below shows how the deviation from the mean of the output under full population decays with the increase in the size of the input population.

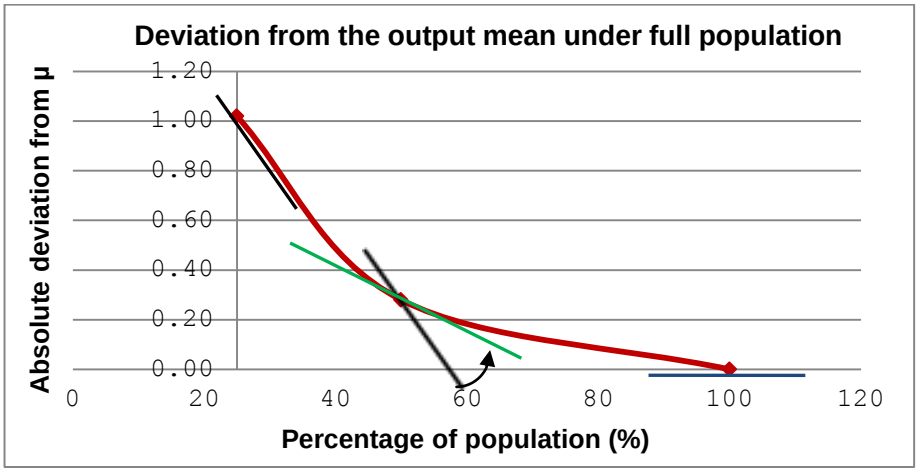


Figure 3.1: A curve which shows the decay of the deviation from the mean of the result under 100% population

The above curve can be interpreted as follows: As the size of input population increases the result is more complete as a larger portion of the full population (100% population) is represented. At the output where one has possibilities the previous analysis applies: As the size of the sample space generated by the model increases, the result is more complete with respect to the space of interest (100% of the possibilities). Now in moving to the second part of the analysis, it was said above that the more complete the result with respect to the space of interest, the more stable is the result. This can be seen from the curve in Figure 3.1: The slope of the curve refers to the *tendency of variation* of the output distribution. It can be seen that the slope of the curve at the three population sizes under consideration (25%, 50% and 100%) is different. As one goes from the smaller population (P1) to the larger population (P2) under consideration the slope is significantly less until it is zero at the 100% population (P3). The larger the size of the input population, i.e. the larger the sample space generated, the less is the tendency of variation and therefore the more stable is the distribution of the output result. Although the experiment performed herein assumes a known full population, the same analysis applies to any model with a target: *The larger the size of the input population, the more complete and stable is the output probabilistic result*. This is the case without knowing the full population where the full population may be unlimited. In Section 3.3.1 the target population is defined and that forms the reference on which the completeness of the result is assessed.

In the case of the model result with 100% population, the full population is the input population to the model and therefore the result is said to be absolutely complete and not relatively complete. For instance, when it is said that a result is relatively complete with respect to the

space of interest, the word “relatively” is used to point to the fact that the input population is only a portion of the full population.

The completeness of a result should not be confused with the spread of the output distribution. It is important to understand that the spread of the output distribution is not the true measure of output completeness and such an assumption would undermine the meaning of completeness. Imagine a result with input populations that account for possibilities at the high bound and the low bound of the full populations but with little consideration for the possibilities in the middle of the range; such a result may have similar spread compared to a complete result, however it is incomplete and does not represent the true uncertainty.

3.2.3 Comparison of different types of WtW results

In the previous discussion the author presented a view of the sample space in its most general form where it simply derives from the distributions in Eq. (3.3). However a deeper understanding of the composition of the sample space is required to describe the form of the different types of WtW results in the space of interest.

The sample space, often denoted as Ω, is composed of all the possible coordinates as defined in Eq. (3.4) and is divided into subsets. A subset of the sample space refers to an event. In the case of the STM one can think about the events of the sample space as subgroups of points in space where each represents one possibility (approximation of a system with some uncertainty). The characterization of the input population with a continuous distribution adds uncertainty to the elements of the input population which are approximations of a real process (e.g. energy loss of an SMR plant). (See Section 3.3.1 for more details on the composition of the input population.) Thus the output which is the sample space is a collection of approximations (subsets) of real systems where each approximation is composed of a set of points in space (with some associated uncertainty). The size of the sample space is measured by the number of events and not the number of points in space which are countably infinite. To estimate the number of different events that can be generated one calculates the number of possible combinations from the discrete sets of values of the input. Let’s assume an algorithm of 4 variables with each variable having an input population of 5 elements, the size of the sample space would be 5^4 which is equal to 625 (all possible combinations). This estimation assumes no associations between the

variables of the model. Thus the actual number of events in the sample space is less because the associations between the variables of the model prohibit some elements from coupling.

Below the form of the different types of WtW results is described in the space of interest:

(a) Determined result

Results of this type form one point in the space of interest and provide no insight what so ever into the uncertainty of the result. Example of a database which generates this type of results is GEMIS.

(b) Random result

In today's models that generate probabilistic results the distributions of the input variables provide a quantitative representation of what is commonly referred to as subjective or epistemic uncertainty (Helton and Davis, 2002). The development of such distributions is mainly judgmental and may involve an expert review process. Nevertheless, the sample space generated by such models represents one subset (possibility) in the space of interest as defined by the STM for a robust WtW result. In fact such models account for one input element at each stage of the STM chain; the evaluation of the STM model under this consideration results in one output possibility. Further, subjective uncertainty does not necessarily improve the reliability of the output. Such type of uncertainty which completely relies on judgement may deteriorate the quality of the input data elements and further disguise the output.

(c) Complete random result

The standardization model accounts for a set of different input elements at each stage of the STM and the output is a large number of subsets in the space of output. For a first generation model a relatively large sample space was achieved. The STM is fed from the measuring tools that were presented in (a) and (b) and forms the first decision-making tool in the field of the source-to-service analysis of automotive fuels. Furthermore, the input data was extracted from the most acknowledged databases in the field and the subjective input to the model was kept at the minimum.

The size of the sample space and therefore the completeness of the result with respect to the space of interest (the space that defines a robust result) is the major element of output reliability.

However, other elements are important. One seeks to achieve a (i) complete as well as an (ii) accurate representation of the space of interest. This, as will be further explained in the following section, implies an accurate characterization of the input uncertainty and an account of the relationships between the variables of the STM.

3.3 The statistical map of the standardization process

In this section the author will study the statistics of the different stages of the standardization process which extends all the way from the sampling of the population to the generation of the output distribution.

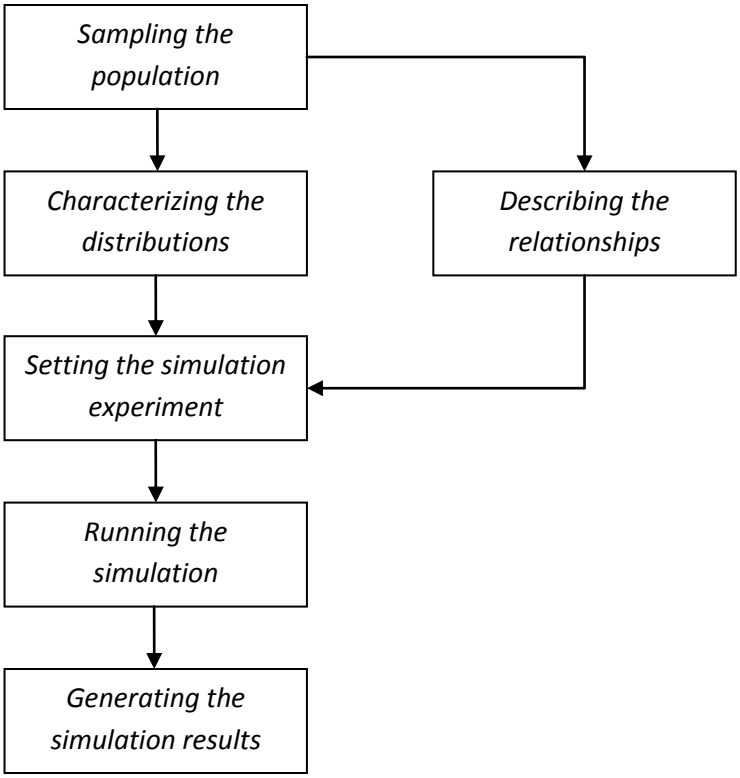


Figure 3.2: The statistical map of the standardization process

3.3.1 Sampling the population

This section forms an important part of our discussion because there may be confusion as to what population the STM output is representing. In looking at Figure 3.2 above one can see that the whole standardization process starts by sampling from some population and there exists another sampling during the simulation run. Thus there are two sampling stages and hence two

populations. The first sampling stage was the main subject of the preceding chapter which discussed the data work required to build an input portfolio for each building block of each chain under study. Before proceeding with the current discussion one needs to define the target population and the sampled population generated through the first sampling stage of the standardization process.

In general terms, the target population is defined as "the totality of elements which are under discussion and about which information is desired" (Mood *et al.*, 1974).The nature of elements is explained by recalling that the goal of the STM is to build up reliability of the output result and integrate the WtW modelling with the process of decision-making. Thus the STM is concerned with (i) the measurement of the uncertainty on a macro level taking into account the variability beyond the subjective variability of the parameters of one database. Such a macro account includes the variability of the so-called modelling elements. The modelling elements are not variables of the STM but descriptive elements which describe the system under study such as:

(1) Database: this refers to the identity of the parameter values (e.g. GREET database)
(2) Process type: hydro, wind or solar; IGCC or coal-fired; among other examples
(3) Process specifications: plant design, type of displaced electricity, distribution pressure, share of process fuels, etc
(4) Transport assumptions: transport mode, transport route, transport distance, etc
(5) System boundaries: land use change, account of process manufacturing, account of upstream fuel supply processes, etc
(6) Methodological choices: modelling structure, allocation methods, heating values (LHV or HHV), etc
(7) Geographic location
(8) Time frame

Thus the difference between one system assumption and another is combined effect of variability in one or more of the modelling elements. And (ii) the STM is concerned with eliminating individualism and thus it samples from different reference models.

In contrast to today's current probabilistic WtW models which generate one event in the sample space for each stage, the STM considers a set of system assumptions at each stage and generates a large number of events in the sample space.

Now it is illustrated that the effect of changes in the modelling elements are different from the effect of subjective uncertainty attached to the input parameters of one database.

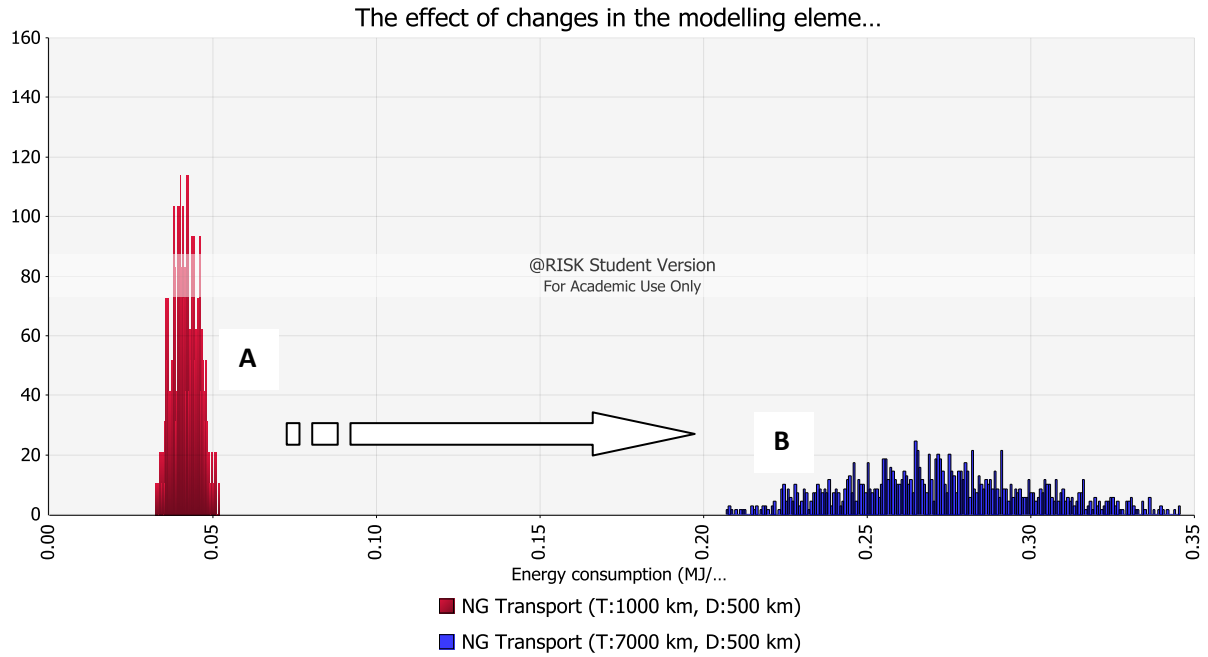


Figure 3.3: The energy consumption for 1000 km and 7000 km NG transport processes in the form of MJ per MJ of CGH2 fuel throughput

To explain, consider two different system assumptions to which arbitrary uncertainty is attached to the parametric assumptions of each process. Both system assumptions were generated from data from JEC (JRC *et al.*, 2008a). For further details on the distribution of each system assumption in Figure 3.3 refer to Appendix B. The 1000 km transport process is within Europe whereas the 7000 km transport process extends from Russia. From taking a closer look at the difference between system assumption B and system assumption A the difference arises from changes in the compression gas turbine (GT) from a European GT to a Russian GT, the transport distance from 1000 km to 7000 km and the pipeline specification (e.g. gas leakage) from a European high pressure line to a Russian high pressure export line.

On the other hand, each of the system assumptions shown in Figure 3.3 above illustrates an account of variation in the parametric assumptions which is considered by the probabilistic

(stochastic) models available today. Such an account is subjective and as mentioned earlier does not necessarily add reliability to the result. It was stated by Maclean and Lave (2003a) that one safe way of managing uncertainty is to ignore it. This avoids the negative consequences of a bad judgement. However, in this respect the STM provides a solution by avoiding individualism. The STM is concerned with the variability of the parameters across different databases and not the subjective uncertainty of the parameters of one database. The account of the parameters of different databases smoothes the standing of individual databases in the analysis. Nonetheless the variability under account by the STM is an inter alia effect of the differences in the modelling elements, including but not restricted to the database, across different reference models.

Such models account for the uncertainty of a specific system assumption, however they do not account for *different* system assumptions. In statistical terms, the variation in the parametric assumptions alone generates different points within one event in the sample space, whereas an account of different system assumptions generates different events in the sample space.

Now in reference to the definition of the target population the author quotes that the information about the elements is actually "desired". This only means that the target population is not necessarily the sampled population. Here the following question applies: What is the difference between the two populations? The target population is the population that one seeks and is under discussion. In the STM the target population is well defined, however it is not real. The target population of the STM as defined earlier is the totality of the different system assumptions that are in literature. Such a population is said to be hypothetical because there is no limit to the assumptions that can be thought of with regards to future understanding and/or a technological breakthrough. To further clarify our point an example of real and hypothetical populations is presented. A real population can be the number of postgraduate students in Oxford University at a certain date; however a hypothetical population can be the sequence of heads and tails obtained by tossing a certain coin an infinite number of times. In the experiment presented in Section 3.2.2 a known population (not hypothetical) was assumed to show how the completeness of the result increases with the size of the input population.

The final point on sampling is that the target population of the STM is unlimited and therefore cannot have a density. In general it is assumed that each element of the input population has a numerical value associated with it and the distribution of these numerical values is given by a

density; however in the case of our target population where the numerical values associated with the system assumptions under discussion represent GHG emissions or energy consumption, the population is hypothetical and does not have limits to allow the creation of density. A problem immediately arises as to how to generate a random sample in a simulation from a population which has no density.

The random sample is defined as follows (Mood *et al.*, 1974):

Let the random variables $x_1, x_2, \dots, x_J$ have a joint density function $f_{x_1,x_2,\dots,x_J}(x_1, x_2, \dots, x_J)$ that factors as follows:

$$f_{x_1,x_2,\dots,x_J}(x_1, x_2, \dots, x_J) = f(x_1)f(x_2) \dots f(x_J) \qquad \text{Eq. (3.9)}$$

where $f(x_J)$ is the density function of x_J. Then $X_{1J}, X_{2J}, \dots, X_{NJ}$ is defined to be a *random sample* of size N from a population with density $f(x_J)$. Thus a random sample cannot be generated in a simulation from a population that has no density and it is not possible to select a random sample from the target population of the STM. Where the simulation stage of the standardization process employs some kind of random sampling, the target population is actually not the input population to the STM. We create a related population called the sampled population and is defined as follows (Mood *et al.*, 1974):

Let $X_{1J}, X_{2J}, \dots, X_{NJ}$ be a random sample from a population with density $f(x_J)$; then this population is called the *sampled population*.

This explains the first sampling as shown in Figure 3.2 and differentiates between the target population that is out there and the population that is under consideration. In the STM the sampled population or the population under consideration is limited to system assumptions extracted from the most acknowledged models in the field. Another restriction on the sampled population is the ability to restructure data of some reference models to fit the building blocks of the STM. This is because the reporting of these reference models is performed on an aggregated level and not all underlying calculations are transparently reported.

This brings us to identifying the population that the STM result is representing and clearly differentiating that from the target population. Making conclusions about a much broader population than the sample actually represents must be avoided (Rumsey, 2007). At this stage the

author stressed on defining the population under consideration to avoid any generalization. Later in the following chapter (Chapter 4) the author will go further in describing the population under consideration by teasing out the distribution of each sampled population. It is important to understand that the author is not claiming that the STM results are complete as no one can do that in a rational sense. As mentioned earlier, the word “complete” is used as a relative term which refers to a far larger size of input population as compared to that of the stochastic WtW models available for decision makers today.

3.3.2 Characterizing the distributions

As noted in the previous section, for the purpose of simulation one needs to define the density of the sampled population from which to generate a random sample. This section will describe the applications used and the assumptions made to characterize the sampled population of each input variable of each chain under study.

3.3.2.1 Data filter

Following the meticulous data work that was described in Chapter 2 one ends up with a set of discrete data for each input variable of each chain under study was obtained. However this set of numerical values is not a sample of the target population (sampled population). These numerical values are not necessarily associated with different system assumptions which are the elements of the target population as defined in Section 3.3.1. The different system assumptions represent different process models (e.g. a model of natural gas reforming plant) and thus the numerical values that represent the same process model should count as one system assumption. The data set generated is therefore filtered by taking the median of all the numerical values that are associated with the same system assumption. Such values are actually from different realizations of the system under study and not necessarily sample elements, i.e., not necessarily associated with different system assumptions.

To demonstrate what was done to achieve a sample of the target population a section of the datasets generated for the WtT-CGH2-NG-Central chain is cut from Appendix L and pasted in Table 3.2. Please refer to the nomenclature list which includes the key that describes the abbreviations used for the different variables and chains under study in the current project.

WtT-CGH2-NG-Central								
	SP-CGH2-NG-Central		ST-CGH2-NG-Central		FP-CGH2-NG-Central		FD-CGH2-NG-Central	
	Energy use	GHG Emissions	Energy use	GHG Emissions	Energy use	GHG Emissions	Energy use	GHG Emissions
	MJ/MJ	gCO_2eq/MJ	MJ/MJ	gCO_2eq/MJ	MJ/MJ	gCO_2eq/MJ	MJ/MJ	gCO_2eq/MJ
GEMIS #1	0.0253	2.2409	0.0025	0.3225	0.1174	55.2848		
GEMIS #2	0.0083	1.5570	0.0197	1.1740	0.1142	55.3035		
GEMIS #3	0.0087	1.7082	0.0382	2.3220	0.1163	55.4478		
GREET #1	0.0631	6.9067	0.0028	0.6062	0.4260	81.9467	0.2117	17.2073
GREET #2	0.0631	6.9067	0.0028	0.6062	0.2759	72.8997	0.2117	17.2073
GREET #3	0.0631	6.9067	0.0028	0.6062	0.3799	79.4178	0.2117	17.2073
JEC #1	0.0400	5.2000	0.2700	20.9000	0.3200	74.1000	0.2200	9.1000
JEC #2	0.0400	4.7000	0.1300	10.9000	0.3200	74.1000	0.2200	9.1000
JEC #3	0.0300	4.7000	0.1300	10.7000	0.3200	73.0000	0.7900	45.3000
JEC #4	0.0400	4.7000	0.2900	18.5000	0.3200	74.1000	0.2200	9.1000
GM #1	0.1000	5.2000	0.3000	21.9000	0.2600	71.7000	0.2000	8.2000
GM #2	0.1000	5.2000	0.3000	21.9000	0.2600	71.7000	0.2400	9.9000

Table 3.2: A section of the datasets generated for the WtT-CGH2-NG-Central chain from Appendix L

In referring to Table 3.2 above the red canvas represents a realization of the system under study from the reference model. The framed example is a realization from the GREET model (version 1.8c). A realization is simply a run of the model under certain assumptions, choices and parameters. The challenging data work that was described in Chapter 2 refers to generating system realizations that are broken down into system assumptions where each system assumption represents an STM process (e.g. fuel production). As one can see from Table 3.2 above the same system assumption may be associated with different realizations. The three realizations that are presented from the GREET model for the system given in Table 3.2 have the same system assumption for feedstock production, feedstock transport and fuel distribution; the difference, however, between the three realizations is in the fuel production process. Therefore the same system assumption can be associated with three different realizations. The green canvas represents a set of numerical values which are associated with the same system assumption. These are filtered by taking the median value. However, the minimum or the maximum value is taken instead of the median value in the case where any of the numerical values of the set is the minimum or the maximum of the whole data set of the stage under study so as not to affect the boundaries of the distribution that are defined by the reference models.

As an example the data set shown under the energy consumption (in MJ per MJ) of the FP-CGH2-NG-Central stage in Table 3.2 will be filtered. Again the section cut from Appendix L

and shown above in Table 3.2 is not complete and is only meant for demonstrative purposes. For the complete data sets and the actual data filter please refer to the Appendix L.

WtT-CGH2-NG-Central	
FP-CGH2-NG-Central	
	Energy use
	MJ/MJ
GEMIS #1	0.1174
GEMIS #2	0.1142
GEMIS #3	0.1163
GREET #1	0.4260
GREET #2	0.2759
GREET #3	0.3799
JEC #1	0.3200
JEC #2	0.3200
JEC #3	0.3200
JEC #4	0.3200
GM-LBST #1	0.2600
GM-LBST #2	0.2600



WtT-CGH2-NG-Central	
FP-CGH2-NG-Central	
	Energy use
	MJ/MJ
GEMIS-System #1	= Min(0.1174,0.1142,0.1163)
GREET-System #1	= 0.4260
GREET-System #2	= 0.2759
GREET-System #3	= 0.3799
JEC-System #1	= Median(0.3200,0.3200,0.3200,0.3200)
GM-LBST-System #1	= Median(0.2600,0.2600)

Table 3.3: An example of a data filter

As one can see from Table 3.3 above, the minimum value was taken from the first data set instead of the median value because the 0.1142 MJ/MJ (GEMIS #2) forms the minimum of the whole data set under the energy consumption of the fuel production stage in the given system. The question that stands herein is why the same system assumption may have different numerical values? As defined earlier in this chapter what makes a system assumption different from another is the inter alia effect of changes in the modelling elements. Thus with no changes in the major modelling elements there is no differentiation of the system assumption which describes a process of the STM. Nevertheless, the numerical value of the same system assumption may insignificantly vary as shown in Table 3.3 due to the facts that (i) as emphasized in Chapter 2 the data elements are extracted in a dependant form, i.e. per MJ of system output, to overcome the structural differences across different reference models and thus the changes in the downstream processes would affect the system assumptions of the upstream processes, (ii) a slight difference in the upstream system of the process fuels may observably affect the numerical value of the system assumption such as in the case presented in the first data set in Table 3.3, however is not considered a change in the modelling elements and does not result in different system assumptions, and (iii) in the cases of stochastic modelling, e.g. JEC model, the standard error of

sampling (refer to Section 3.3.4.3 for the definition of the standard error) may be a source of observable variation in the numerical value of the same system assumption under different realizations.

The data sets are filtered to generate a sample of the target population for each stage of the chain under study and avoid the creation of false densities which count the same system assumption more than once. The data sample would then be inconsistent with the definition of the elements of the target population and the density function that is generated from the sampled population would not be realistic.

3.3.2.2 Distribution fit

After the data filtration one ends up with a sample of different system assumptions for each stage (sampled population). As mentioned earlier in Section 3.3.1 the sampled population can have a density and this is estimated by characterizing the distribution of the numerical values associated with the sampled elements. After estimating the properties of the sampled population by fitting distributions to the data sample, one can generate random samples from the density function of the sampled population in a simulation. More specifically, the sample drawn from the population is generated by an algorithm (random number generator) and this is not actually random but poses the qualities of random numbers which are uniformly distributed. For the operation of random number generators in a simulation the density function of the population from which we are sampling is required.

In the standardization process one is not defining uncertainty to the input by personal judgement but characterizing the uncertainty that stems from the changes in the modelling elements across the reference models. Depending on personal judgement it is amenable to *define* a simple density function (triangular, normal or uniform) to an input parameter, however, the use of complex density functions for the accurate characterization of the distribution of different system assumptions cannot be performed without an advanced software tool.

The STM employed the BestFit® which is wholly integrated into @Risk v5.7 (Palisade, 2010a) as the distribution fitting feature to fit the input samples to various types of probability distributions. In @Risk one can choose from over thirty different continuous functions to fit a

given sample. Furthermore, the application superimposes the basic statistics of the input data and the fitted distribution and ranks them to choose the best fit as shown in Figure 3.4 below.

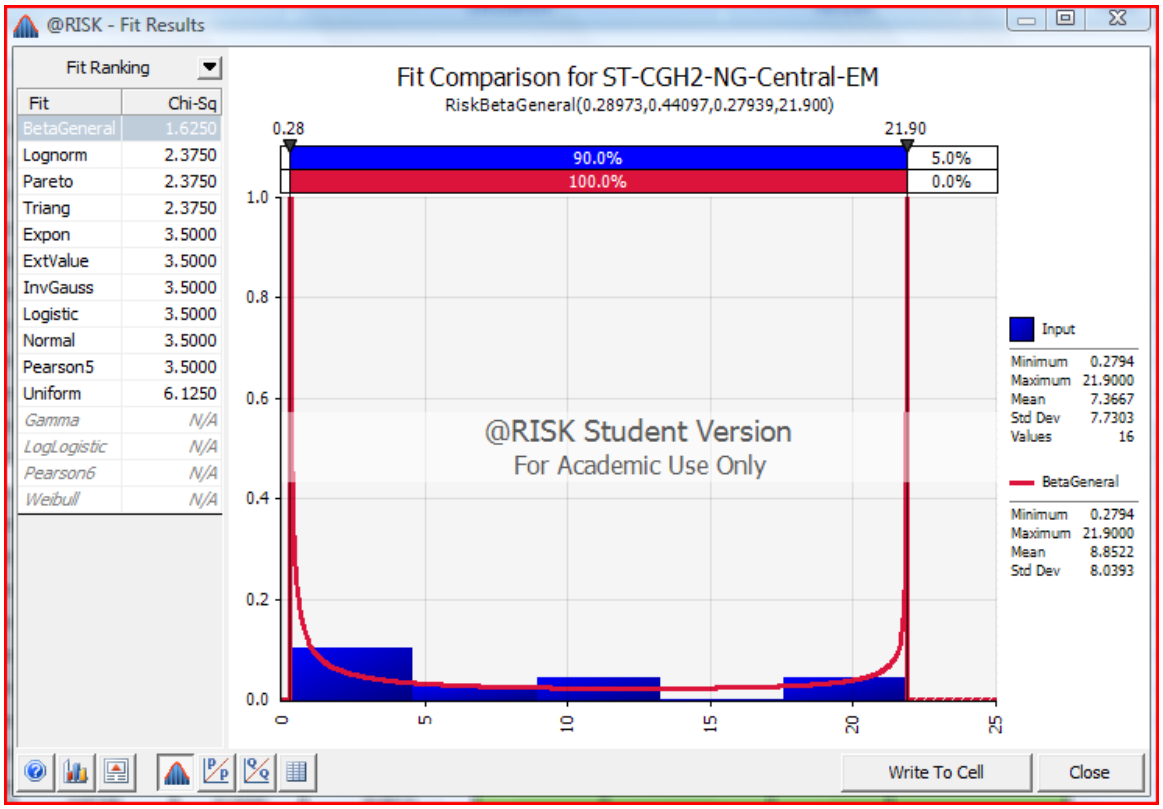


Figure 3.4: The fit results panel showing a comparison of the fitted distributions for the GHG emissions of the ST-CGH2-NG-Central stage. Note: the shape of the distribution fit may look like a numerical artefact. This may clearly show an effect on the shape of the simulation output as in Figure 5.20. Nevertheless, the outcomes of main interest from the distribution fitting are statistics such as the mean and standard deviation.

A good fit has nearly (i) the same mean and standard deviation as the input sample and (ii) all of its population is bound within the sample interval. The chi-square test is chosen to measure the goodness of fit and select the best fits. Further among the best fits one chooses the distribution that has more of its population bound within the input sample interval. The use of the truncate function to limit the interval of the fitted distribution to the input sample interval is avoided because it obscures the statistics of the distribution. The truncation function is only used when the interval of the fitted distribution is non-realistic such as in Figure 3.5.

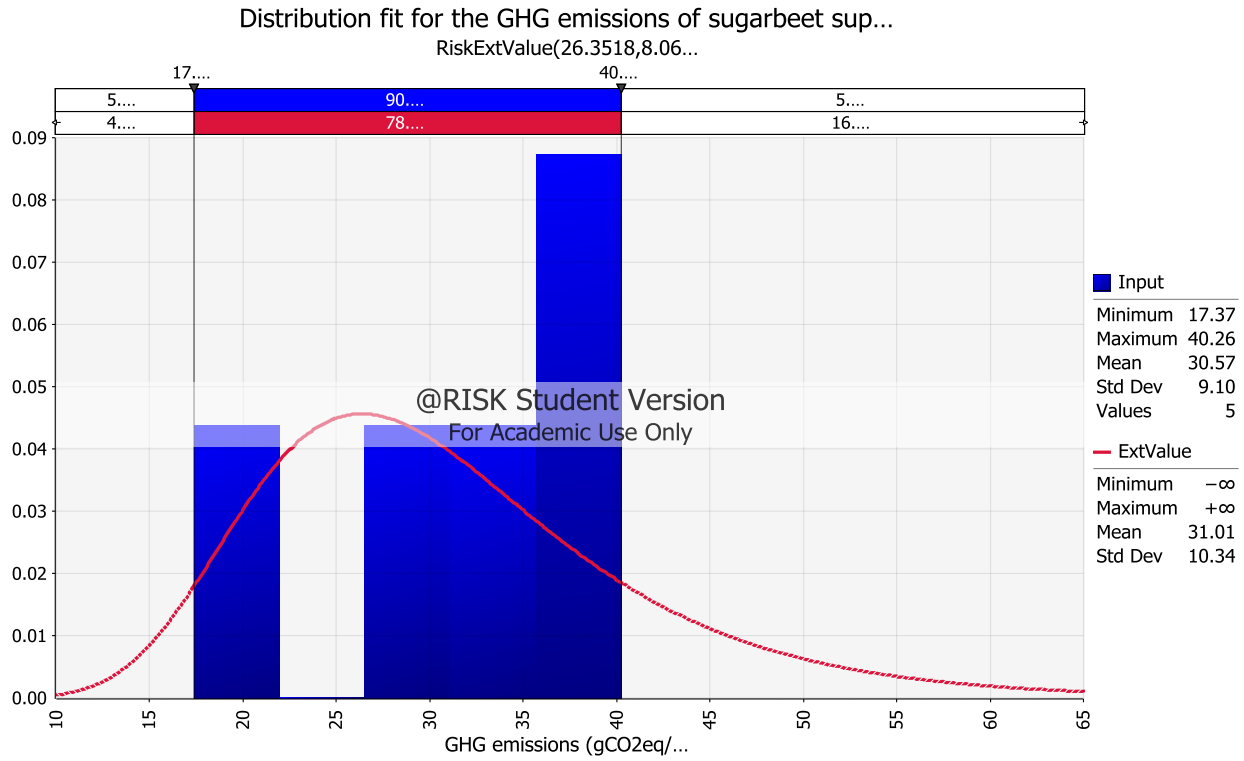


Figure 3.5: An example of a case where we need to truncate the fitted distribution: The distribution function for the GHG emissions of sugarbeet supply

The lower bound of the fitted distribution is negative and this is not allowed in the process under evaluation. The lower bound of the GHG emissions distribution function as depicted in Figure 3.5 is infinitely negative whereas in reality the process of sugarbeet production and transport does not have a carbon sink to result in negative GHG emissions.

In the limited cases where the sample size is less than five it falls short of the requirements for a distribution fit by @Risk and the distribution is defined by inspection. In such cases the normal distribution was assumed by default to copy the main statistics of the input sample. Although the defined distribution is an assumption and does not accurately characterize the input sample, the normal distribution in particular minimizes the associated error. In fact the variance of the model output stems from the variance of the model inputs and this is not affected by the accuracy of the probability distribution. Thus the assumption of a normal distribution ensures that the variance which is the most important statistical element in the STM is accurately defined.

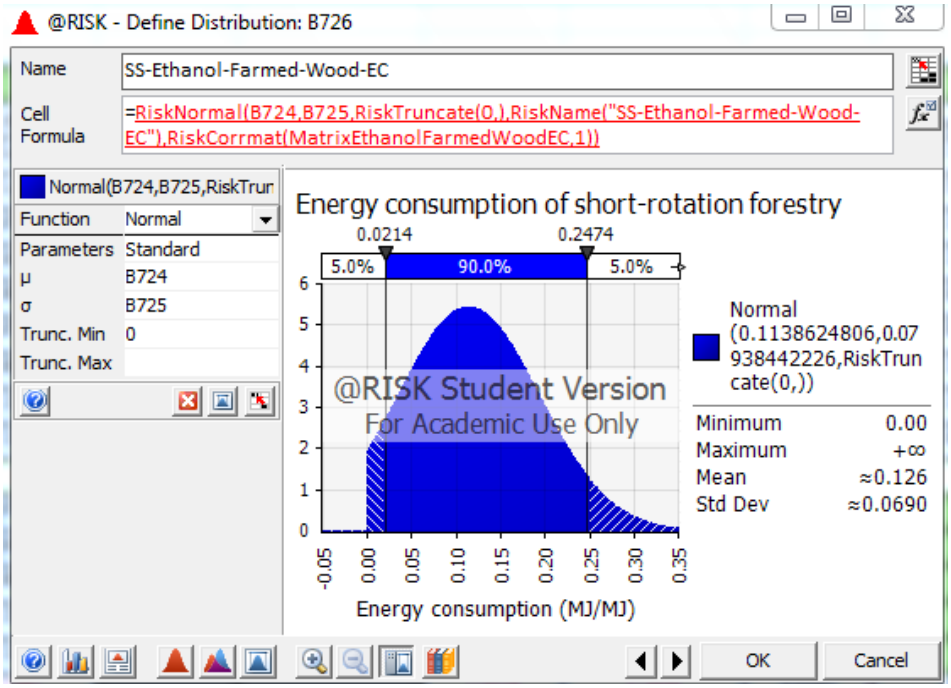


Figure 3.6: The @Risk Define Distribution tool where distribution functions are defined by arguments

Each density function is defined by a set of arguments and those of the normal distribution are the mean (μ) and standard deviation (σ) as shown in Figure 3.6 above.

Importantly, in the cases where the observed uncertainty of a certain stage in one chain (the number of different system assumptions accounted by that stage) is significantly less in another chain which integrates the same stage, the distribution that represents the largest account of uncertainty for that stage is assumed. This is done to maintain uniformity in the uncertainty of the same stage across different options.

3.3.2.3 Fit statistics

As shown in Figure 3.4 the Distribution Fitting tool generates a serious of fits from which to choose the best fit. Herein we ask the following question: How good is the match between the probability density function and the histogram of the input data? Special tests exist for special distributions; however, given that a large number of different distributions are being fitted to the data sample a test which applies in all situations should be employed. This test, the chi-square goodness-of-fit test, was established by Pearson in 1900 and formed one of the cornerstones of modern statistics (Morgan, 1999). This was used to choose among the different fits generated by

@Risk. In Figure 3.4 one can see that the chi-square statistic is calculated and listed with the fitted distributions starting with the best match, smallest chi-square statistic.

For any distribution one can divide up the range of the random variable into M intervals; each interval is shown by the histogram of the input data (for example see Figure 3.4 and Figure 3.5). The chi-square statistic is simply comparing the observed number of values in each interval (frequency of each interval) with the number one would expect from the fitted distribution:

$$X^2 = \sum_{i=1}^{M} \frac{(O_i - E_i)^2}{E_i} \qquad \text{Eq. (3.10)}$$

where O_i and E_i denote the observed and expected number of values in the ith interval. The smaller is the chi-square statistic (X^2), the better is the fit.

The more accurate the characterization of the input samples the more real is the sample space which derives from the input distributions. The concept here is referred to as RIRO (Real Input, Real Output) and follows the same concept as GIGO (Garbage In, Garbage Out) which applies to any model. In the following section the author shows how the consideration of the relationships between the input distributions of the model also affects the reality of the output modes which make up the sample space.

3.3.3 Describing the relationships between variables

Having characterized the resulting uncertainty by probability distributions the Monte Carlo sampling technique is employed using the @Risk v5.7 simulation software to propagate the inherent variability throughout the full chain of fuel production, distribution and use. In brief the Monte Carlo sampling randomly generates samples from the input distributions of the model where the size of each sample (N) is equal to the number of iterations in the simulation. Each combination between the generated samples results in one output mode. Nevertheless, the combinations from the generated samples may not be completely random. There may be relationships which drive the input risks to move non-independently from each other. Whether direct or aggregate, involving simple mathematics or greater complexities, it is these relationships between variables that need to be expressed in a model to ensure a realistic output. Such relationships are described by a principle relational element known as correlation.

The function of the WtT part of the STM is defined as follows:

$$f_{WtT}(\mathbf{x}) = f_{WtT}(x_1, x_2, \dots, x_J) = \sum_{i=1}^{J} x_i \qquad \text{Eq. (3.11)}$$

where **x** is the input vector (see Section 3.2.1) and J is the number of decision variables in the WtT part of the STM. Now the combinations from the samples generated (further details on Monte Carlo sampling is given in Section 3.3.4) from the input variables contained in **x** such as:

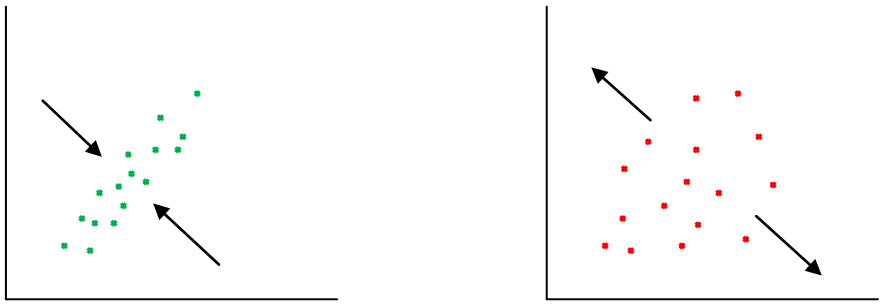
$$X_{11}, X_{12}, \dots, X_{1J} \qquad \text{Eq. (3.12)}$$

should follow the correlations between the input variables. Eq. (3.12) represents one combination. In fact, the reality of the output modes significantly stands on how well we account for the correlations between the input variables of the STM.

Generally speaking the correlation between two variables describes tendencies of paired behaviour. For example when variable A has a low value there is a tendency for variable B to be low as well. Nevertheless, such a dependent behaviour is a result of the common sources of variance. For example, the GHG emissions from the biomass feedstock supply is a common source of variance between the GHG emissions from the fermentation stage, which include the GHG emissions from the upstream supply of biomass feed loss, and the GHG emissions from the biomass feedstock supply stage. In simple algebraic terms if A + B = C and A = D, then A is a common source of variance between C and D.

3.3.3.1 The principal relational element

To see the correlation between two variables (e.g. x_1 and x_2) a scatter plot diagram is produced where each dot represents one pair from the samples. As demonstrated in Figure 3.7 below: (a) the points in the first cloud are tightly clustered around a line which means that there is a strong linear association between the two variables; (b) the clustering is much loser and the cloud is formless which means that there is nearly no association between the two variables.



(a) Strong association **(b) Nearly no association**

Figure 3.7: Summarizing a scatter diagram

The figure above shows how the correlation between two variables can be directly interpreted graphically. "If there is a strong association between two variables, then knowing one helps a lot in predicting the other. But when there is a weak association, information about one variable does not help much in guessing the other" (Freedman *et al.*, 1997). Thus if there is a strong correlation between two variables, then sampling from one variable governs the sampling from the other variable in a simulation. But when there is a weak association, sampling from one variable has little influence on the sampling of the other.

Following the introduction of the graphical interpretation of correlation between two variables the statistical measure of correlation, the correlation coefficient *r*, is introduced. It is defined as:

$$r = \frac{\boldsymbol{s}_{x_1 x_2}}{\boldsymbol{s}_{x_1}\boldsymbol{s}_{x_2}} \qquad \text{Eq. (3.13)}$$

where $\boldsymbol{s}_{x_i}$ is the standard deviation of x_i values:

$$\boldsymbol{s}_{x_i} = \sqrt{\frac{\sum(x_i - \overline{x}_i)^2}{N-1}} \qquad \text{Eq. (3.14)}$$

where $\overline{x}_i$ is the mean of x_i values and *N* is the sample size; and $\boldsymbol{s}_{x_1 x_2}$ is the covariance of x_1-x_2 values:

$$\boldsymbol{s}_{x_1 x_2} = \frac{\sum x_1 x_2}{N} - \frac{\sum x_1 \sum x_2}{N^2} \qquad \text{Eq. (3.15)}$$

In Appendix L the scatter plot for GHG emissions of SP-CG-Crude-Oil and of ST-CG-Crude-Oil for the conventional gasoline from crude oil chain are plotted. The scatter plot shows graphically how the two variables for the production and transport stages are associated. From the plot one can see that the cloud is formless and there is clearly no significant association. The correlation coefficient can be measured by the CORREL function in Excel and is between 0 and 1 (or -1 in case of a negative correlation): The closer *r* is to 1, the stronger the association between the two variables, and the more tightly clustered are the points around a line. A correlation of 1 is a perfect correlation where all points lie exactly on a line and there is a perfect linear relationship between the variables. The closer *r* to 0, the weaker the association between the two variables, and the more loosely clusters the points around a line. The correlation coefficient of the relation presented in Figure 3.8 is 0.103 which reflects the graphical interpretation of the association between the two variables as being weak.

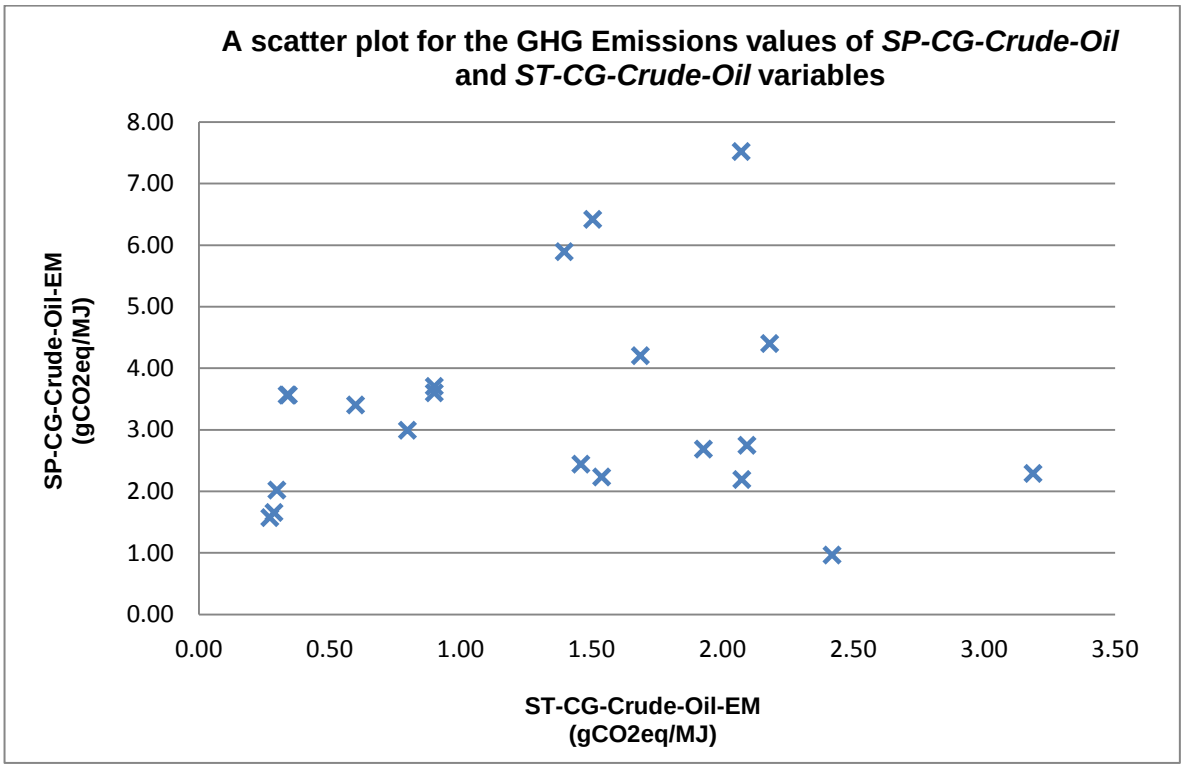


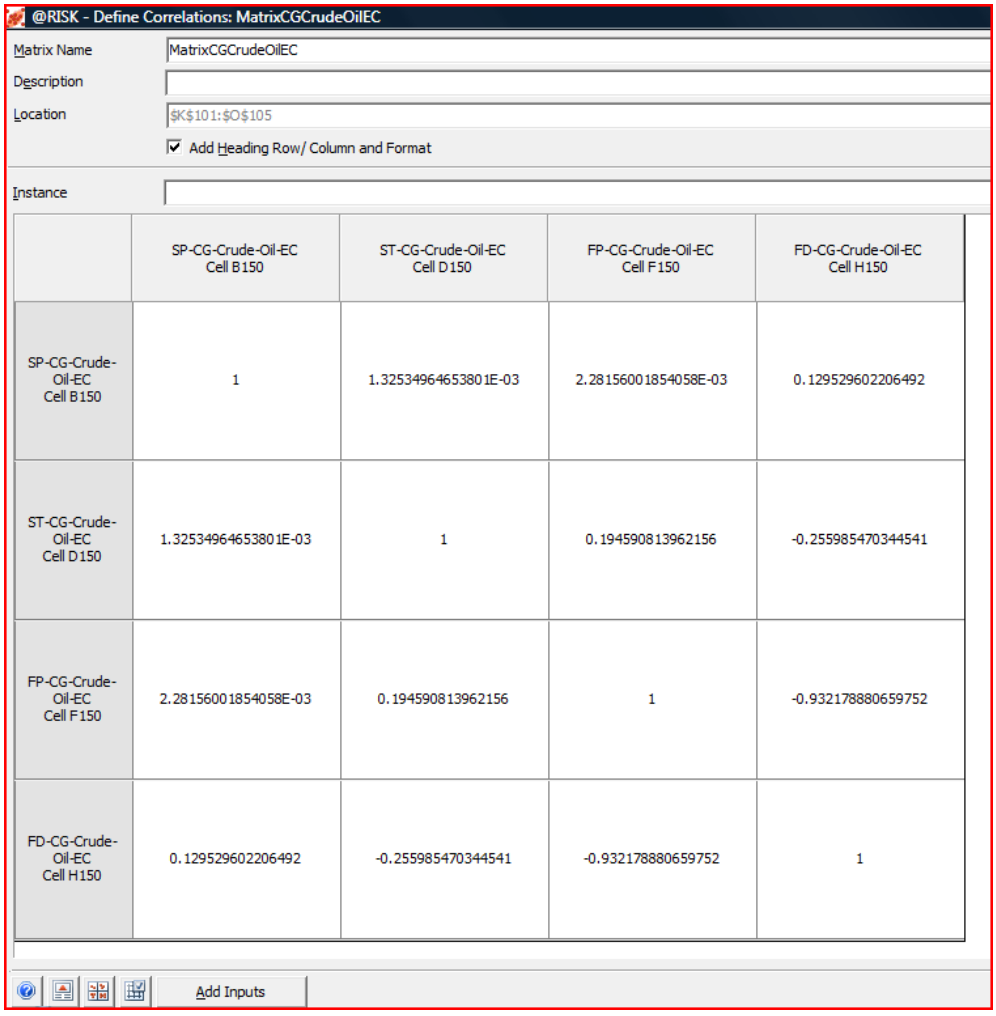
Figure 3.8: A scatter plot of the GHG emissions for the Feedstock Production (SP) and Feedstock Transport (ST) stages of the conventional gasoline from crude oil chain from Appendix L

Each point in the Graph above represents a pair of values from one system realisation (for the definition of a realisation see Table 3.2). Data is extracted from the reference databases in the form of complete realisations, where possible, to study the tendencies of paired behaviour

between the variables of an STM chain one pair at a time as shown in Figure 3.8 and define the correlation coefficients in the form of a correlation matrix in the settings of the simulation.

3.3.3.2 Defining the correlation matrix

As mentioned in the previous section the correlations between the WtT variables of an STM chain are measured one pair at a time using the set of realisations built up from the reference models. The correlation coefficients should be then combined into a correlation matrix which defines the correlations between the variables across the WtT chain under study (e.g. the production and distribution of conventional gasoline). The Define Correlations tool in @Risk is used to enter the correlations of the variable pairs in a matrix as shown in Figure 3.9 below.



	SP-CG-Crude-Oil-EC Cell B150	ST-CG-Crude-Oil-EC Cell D150	FP-CG-Crude-Oil-EC Cell F150	FD-CG-Crude-Oil-EC Cell H150
SP-CG-Crude-Oil-EC Cell B150	1	1.32534964653801E-03	2.28156001854058E-03	0.129529602206492
ST-CG-Crude-Oil-EC Cell D150	1.32534964653801E-03	1	0.194590813962156	-0.255985470344541
FP-CG-Crude-Oil-EC Cell F150	2.28156001854058E-03	0.194590813962156	1	-0.932178880659752
FD-CG-Crude-Oil-EC Cell H150	0.129529602206492	-0.255985470344541	-0.932178880659752	1

Figure 3.9: The Define Correlations window where the correlations between the input distributions are defined

A correlation matrix such as that shown in Figure 3.9 describes the relationships between the WtT variables of the STM. In the next section it will be shown how the simulation runs with

embedded correlations between the input variables without affecting the randomness of sampling.

However, the compilation of the correlation estimates into a matrix as shown in Figure 3.9 does not necessarily generate a consistent matrix. An invalid matrix specifies inconsistent simultaneous relationships between three or more inputs. An example of an inconsistent correlation matrix is: correlate input A and B with a coefficient of +1, B and C with a coefficient of +1, and C and A with a coefficient of -1. This example is clearly illegal but invalid matrices are not always this obvious. As such a correlation matrix entered in the correlation window as shown in Figure 3.9 is automatically checked for consistency when the OK button is clicked. In the case of an invalid matrix, @Risk adjusts the coefficients to generate the closest valid matrix. This is done prior to entering the matrix in Excel (see the @Risk correlations table in Figure 3.10) and adding RiskCorrmat functions for each input in the matrix. Figure 3.10 below shows an example of a correlation matrix that was adjusted by @Risk. Only 5 out of 47 entered matrices were identified as inconsistent and adjusted.

Measured Correlations	SS-CGH2-Biomass-EM in C382	FP-CGH2-Biomass-EM in G382	FD-CGH2-Biomass-EM in I382
SS-CGH2-Biomass-EM in C382	1		
FP-CGH2-Biomass-EM in G382	0.827485374	1	
FD-CGH2-Biomass-EM in I382	-0.382118498	0.303116643	1
@RISK Correlations	SS-CGH2-Biomass-EM in C382	FP-CGH2-Biomass-EM in G382	FD-CGH2-Biomass-EM in I382
SS-CGH2-Biomass-EM in C382	1		
FP-CGH2-Biomass-EM in G382	0.7871956	1	
FD-CGH2-Biomass-EM in I382	-0.3635134	0.2883581	1

Figure 3.10: A snap shot from the WtT worksheet showing an example of an inconsistent matrix that was adjusted by @Risk

The RiskCorrmat function identifies the location in the matrix of the coefficients used in correlating the distribution function that is attached to the RiskCorrmat function in the model input cell as shown in Figure 3.11 below.

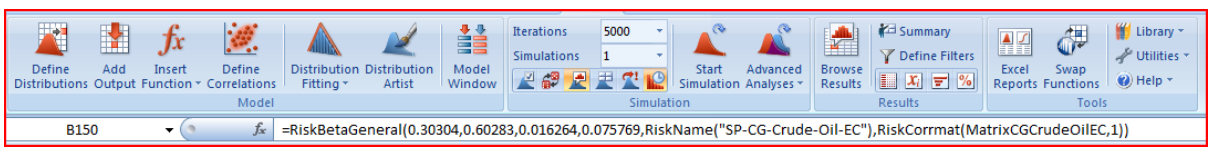


Figure 3.11: A snap shot showing the equation of a WtT model input cell

3.3.3.3 The correlation between the STM outputs

In the previous sections the methods used to estimate the correlations between the WtT input variables of the STM were presented. This type of correlation is an aggregate of various sources of covariance and involves complexities which do not allow for the estimation by simple mathematics. The method employed relies on a set of system realisations built up from the reference models. However, the accuracy to which the correlations are estimated is always limited by the number of realizations and a significant error cannot be avoided.

On the other hand, in this section the author presents the methods used to estimate the correlations between the STM outputs. This type of correlation is direct and involves simple mathematics. In Chapter 4 the uncertainty of the output results is probed to determine the major factors of variance for each chain. In fact, among the major factors of variance the only common source of variance between the outputs of the different STMs is the vehicle performance. Thus there is one source of covariance between the STM outputs. Thus for STM A and STM B the correlation between the outputs (e.g. energy consumption) can be estimated as follows:

Correl (A, B) = Correl (V1P, A) * Correl (V2P, B) * Correl (V1P, V2P)

The correlation between the STM output (WtW) and the vehicle performance (TtW) can be estimated by sample based sensitivity analysis. On the other hand, the correlation between the performance of vehicle 1 of option A (V1P) and vehicle 2 of option B (V2P) is accurately measured as the correlation between the assumptions of the two variables under the combined changes in the modelling elements (such as the vehicle weight and driving cycle) . The relation between two samples of vehicle performance is illustrated in Figure 3.12.

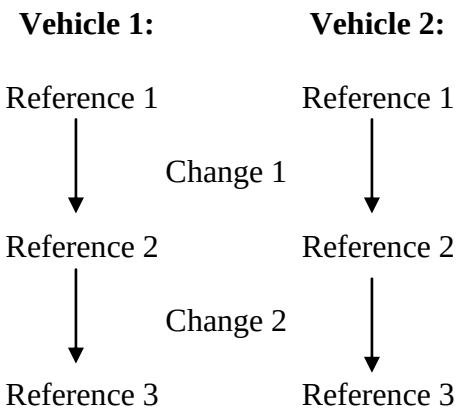


Figure 3.12: The relation between assumptions from variables of different models

3.3.4 Running the simulation

After the input cells are complete as shown in Figure 3.11 the designated output cells are equated by the model function and added as simulation outputs using the Add Output command. The function in Eq. (3.11) applies only to WtT models which generate results on a WtT basis. The WtW model, however, is an aggregate of the WtT model and the TtW stage as shown in the following equations:

$$
\begin{aligned}
y_{WtW} &= f_{WtW}(\mathbf{x}) \\
&= f_{WtW}(x_1, x_2, \dots, x_J, x_K) \qquad \text{Eq. (3.16)} \\
&= x_K\left[1 + f_{WtT}(x_1, x_2, \dots, x_J)\right] \\
v_{WtW} &= f_{WtW}(\mathbf{u}, x_K) \\
&= f_{WtW}(u_1, u_2, \dots, u_J, u_K, x_K) \qquad \text{Eq. (3.17)} \\
&= u_K + \left[x_K \times f_{WtT}(u_1, u_2, \dots, u_J)\right]
\end{aligned}
$$

where,

	Description	**Unit (type I)**	**Unit (type II)**
$f_{WtT}(x_1, x_2, \dots, x_J)$	WtT energy loss	MJ/MJ_{fuel}	MJ/MJ_{fuel}
x_K	TtW energy loss	MJ/km	MJ/MJ_W
$f_{WtW}(x_1, x_2, \dots, x_J, x_K)$	WtW energy loss	MJ/km	MJ/MJ_W
$f_{WtT}(u_1, u_2, \dots, u_J)$	WtT GHG emissions	gCO_2eq/MJ_{fuel}	gCO_2eq/MJ_{fuel}
u_K	TtW GHG emissions	gCO_2eq/km	gCO_2eq/MJ_W
$f_{WtW}(u_1, u_2, \dots, u_J, u_K, x_K)$	WtW GHG emissions	gCO_2eq/km	gCO_2eq/MJ_W

Table 3.4: A key for Eq. 3.16 and Eq. 3.17 also showing the two types of results generated in the current project

Finally the simulation settings are adjusted as desired and the simulation is run by @Risk when the Start Simulation command is clicked. The following sections aim to describe the simulation process and discuss two important settings: (1) The number of iterations; and (2) The sampling technique?

3.3.4.1 Simulation

As mentioned earlier, simulation is a useful tool for describing a mathematically formulated model. Through simulation one can ask "what if?" questions about the modelled process without having to experiment on the actual process itself. The process under study is simulated a large number of times (e.g. 5000). Each simulation is equally likely, and is referred to as a realization of the process—also known as iteration. For each realization, all of the model variables are sampled (i.e., a single random value is selected from the distribution describing each variable). This generates a large number of separate and independent results, each representing a possible outcome of the system, and which collectively represent the spatial variability of the output (sample space) to certain proximity. The type of simulation presented herein and performed by @Risk is called Monte Carlo simulation.

3.3.4.2 Monte Carlo simulation

In probabilistic terms the Monte Carlo simulation is a sampling procedure that is used to develop a mapping from analysis input to analysis results. Specifically, a total sample

$$\mathbf{x}_i = [x_{i1}, x_{i2,} \ldots, x_{iJ}],\ i = 1, 2, ..., N \qquad \text{Eq. (3.18)}$$

of size N is randomly generated in consistency with the distributions in Eq. (3.3).

Let J = 4 and N = 4 an example of a total sample would be:

$$\begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} \\ X_{21} & X_{22} & X_{23} & X_{24} \\ X_{31} & X_{32} & X_{33} & X_{34} \\ X_{41} & X_{42} & X_{43} & X_{44} \end{bmatrix} \qquad \text{Eq. (3.19)}$$

Once the total sample in Eq. (3.18) is generated, evaluation of f creates the following mapping from analysis inputs to analysis results:

$$[\mathbf{x}_i, y_i],\ i = 1, 2, ..., N \qquad \text{Eq. (3.20)}$$

where,

$$y_i = f(\mathbf{x}_i) \qquad \text{Eq. (3.21)}$$

Given the example in Eq. (3.19) and in a WtT model the results would be:

$$y_{WtT} = f_{WtT}\begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} \\ X_{21} & X_{22} & X_{23} & X_{24} \\ X_{31} & X_{32} & X_{33} & X_{34} \\ X_{41} & X_{42} & X_{43} & X_{44} \end{bmatrix} = \begin{bmatrix} X_{11}+X_{12}+X_{13}+X_{14} \\ X_{21}+X_{22}+X_{23}+X_{24} \\ X_{31}+X_{32}+X_{33}+X_{34} \\ X_{41}+X_{42}+X_{43}+X_{44} \end{bmatrix} = \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \end{bmatrix} \quad \text{Eq. (3.22)}$$

This mapping then provides a basis for the evaluation (not mathematical) of the integral in Eq. (3.5), i.e., uncertainty analysis. The distribution of the simulation results $[Y_1, Y_2, \dots, Y_N]$ provides the most complete representation of the uncertainty in y that derives from the distributions in Eq. (3.3) and hence the sample space. In other words, the distribution of the simulation results $[Y_1, Y_2, \dots, Y_N]$ is an approximation of the density function f_y in Eq. (3.5). The spatial plot of $[\mathbf{x}_i, y_i]$, therefore, provides the most complete representation of the sample space that derives from the distributions in Eq. (3.3). Nevertheless, the Monte Carlo simulation also provides a basis for the evaluation of the effects of individual elements of **x** on Eq. (3.1), i.e., sensitivity analysis.

Now the degree of completeness to which the distribution that is mapped out represents the density function in Eq. (3.5) was referred to in Section 3.2.2 as the stability of the output distribution with respect to the sample space. This was differentiated from the stability of the output with respect to the space of interest or the universe under discussion. The size of the total sample (N) in practice that is required to closely approximate the sample space and therefore the distribution of y that derives from the distributions in Eq. (3.3) is in multiples of 10,000. This reflects the size of the computation performed by @Risk to evaluate the model function as demonstrated in Eq. (3.22) on a small sample. However, as yet there remains the question, what should the sample size N be for an accurate approximation? To get a handle on this standard error is examined.

3.3.4.3 Standard error

As mentioned in Section 3.3.4.2 above "the distribution of the simulation results $[Y_1, Y_2, \dots, Y_N]$ is an approximation of the density function f_y in Eq. (3.5)". The mean of the output sample is defined to be:

$$\overline{Y} = \frac{1}{N}\sum_{i=1}^{N} Y_i \qquad \text{Eq. (3.23)}$$

where the output sample $[Y_1, Y_2, \dots, Y_N]$ is a random sample from the density function $f_y(y)$, which has mean μ_y and finite variance ${\sigma_y}^2$. In light of using the value of $\overline{Y}$ to estimate μ_y, the degree to which the distribution of $\overline{Y}$ is *centred* about μ_y reflects the degree to which the distribution of the simulation output Y_i closely approximates the function $f_y(y)$ which is derived from the distributions in Eq. (3.3). The degree to which the distribution of $\overline{Y}$ is *centred* about μ_y is measured by the variance of $\overline{Y}$:

$${\sigma_{\bar{Y}}}^2 = \frac{1}{N}{\sigma_y}^2 \qquad \text{Eq. (3.24)}$$

and is called the sampling error, also known as the standard error. From Eq. (3.24) it is really seen that the larger the size N of the output sample, the more complete is the representation of the output function $f_y(y)$ that derives from the distributions in Eq. (3.3). The Monte Carlo simulation by @Risk provides the option of monitoring the convergence of the output statistic to a specified limit of tolerance with a certain level of confidence. The number of iterations N was set to "auto" where the results are recursively tested during the simulation run for convergence to a tolerance limit of ±2% until a confidence level of 97.5% was achieved. The convergence test was performed on the main statistics of the output such as the mean and standard deviation. Note: the sampling technique under which the simulation was run is called Latin Hypercube Sampling (LHS). The next section will describe the different types of sampling methods provided by @Risk and the impact of the chosen sampling technique on the convergence of the output statistics.

3.3.4.4 Sampling method

As mentioned in Section 3.3.4.2, in Monte Carlo analysis a sample of size N (Eq. 3.18) is randomly generated in consistency with the distributions of the elements of the input vector. However, what is the sampling method that must be used to generate the sample in Eq. (3.18)? This is an important factor in determining the number of iterations N required to accurately recreate an input distribution through sampling. The completeness of the representation of the output sample space depends on how complete is the sampling from the input distributions.

The two methods of sampling that are provided by @Risk are: (i) Simple Random sampling, simply known as Monte Carlo sampling and (ii) Latin Hypercube sampling. To provide a perspective on the use of Latin Hypercube sampling to generate the sample in Eq. (3.18) in the current project the different sampling methods will be reviewed. The understanding of the concept of cumulative probability is a pre-requisite to understanding the difference between the two sampling procedures presented herein. Details for both are now covered.

Any probability distribution in the simulation model can be expressed in a cumulative form. A cumulative curve is typically scaled from 0 to 1 on the y-axis, with y-axis values representing the cumulative probability up to the corresponding x-axis value. For representative purposes a cumulative probability curve was developed and presented in Figure 3.13 below.

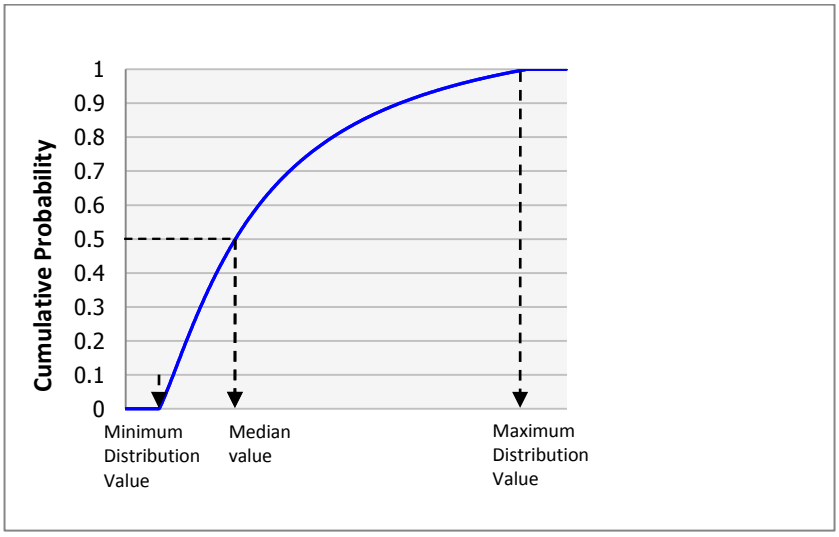


Figure 3.13: A representation of a cumulative probability curve

As shown in the figure above, the 0.5 value on the y-axis represents the cumulative probability up to the median value on the x-axis. The 0.5 cumulative value is the point of 50% cumulative probability (0.5 = 50%) where 50% of the values in the distribution fall below the median value and 50% are above. The 0 cumulative value is the minimum value with no values below this point, and the 1.0 cumulative value is the maximum value with 100% of the values falling below this point. Now the reason why the concept of the cumulative probability curve is so important for the understanding of the sampling procedure is that the 0 to 1.0 scale of the cumulative curve is the range of the possible random numbers generated during sampling. The random numbers are often called pseudo-random numbers because they are generated by reproducible algorithmic processes rather than in a truly random manner. However the method of generating random numbers is taken for granted and discussed no further.

The following discussion will shed the lights on the difference between a typical Monte Carlo sampling and a Latin Hypercube sampling. In a typical Monte Carlo sampling sequence, the computer will generate a random number between 0 and 1 with any number in the range equally likely to occur. This number is used to select a value from the cumulative curve. For instance, when sampling from the distribution in Figure 3.13, if a random number of 0.5 is generated the median value is selected and sampled out. Now although the distribution of the random numbers generated in a number of iterations should be uniform (all random numbers are equally likely), the shape of the cumulative curve, which is based on the shape of the input probability distribution, will cause more likely outcomes to be sampled more such that with a large number of samples N the probability distribution is recreated. However, in using a Monte Carlo sampling method there is no guarantee that a sample element will be generated from any particular range of the distribution. As illustrated in Figure 3.14 below, the performing of a small number of iterations by simple random sampling could result in clustering.

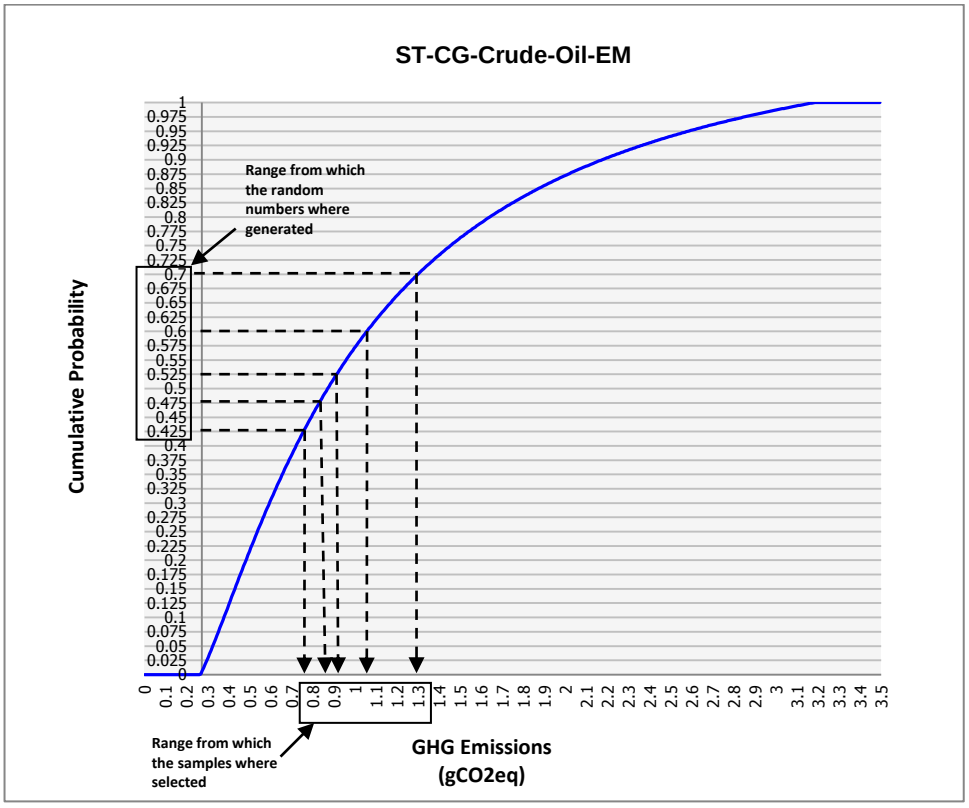


Figure 3.14: An illustration of the sampling of 5 random samples from the ST-CG-Crude-Oil-EM distribution by the Monte Carlo sampling method

As shown in the illustration above, each of the 5 samples drawn falls in one range of the distribution and the values in the other ranges of the distribution are not represented in the samples. One does not expect to accurately regenerate a distribution from 5 samples; however, we show a very small number of samples in Figure 3.14 to illustrate the possible *clustering effect* of simple random sampling.

Latin Hypercube sampling, first presented by Mckay *et al.* (1979) for modelling the blow down depressurization of a straight water pipe, is designed to accurately recreate the input distribution through sampling in "fewer" iterations when compared with the Monte Carlo method.

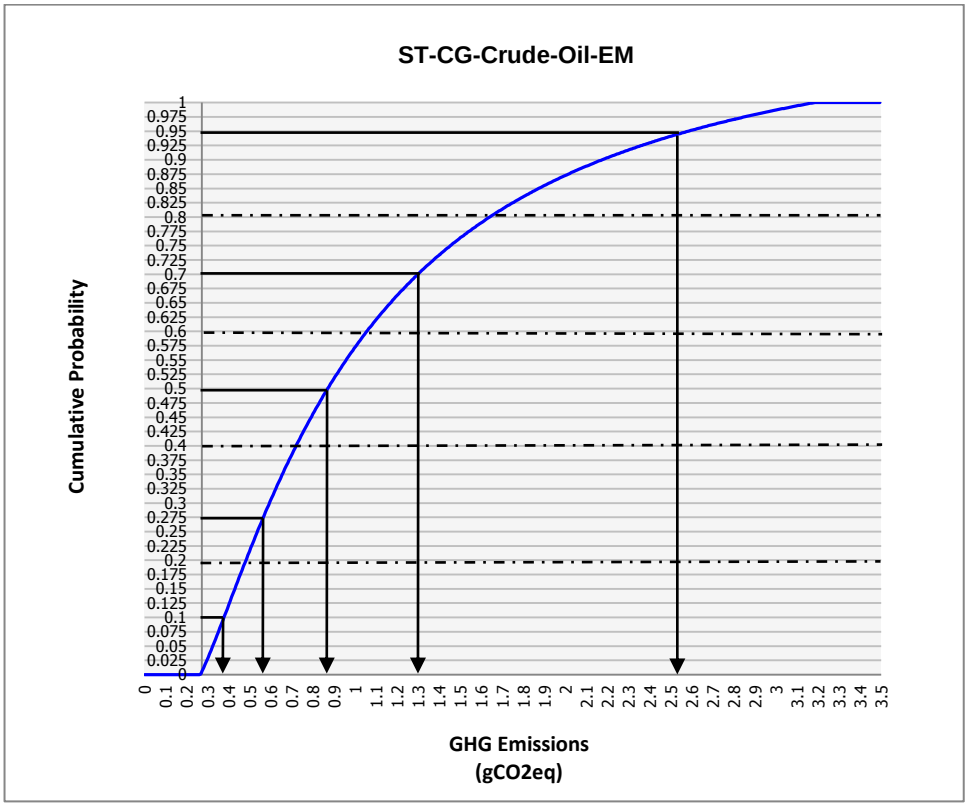


Figure 3.15: An illustration of the sampling of 5 random samples from the ST-CG-Crude-Oil-EM distribution by the Latin Hypercube sampling method

As illustrated in Figure 3.15 above, the cumulative curve range is divided into *N* stratas and one random number is generated from each strata. This procedure eliminates the clustering effect by forcing the inclusion of specified ranges of the distribution while maintaining the probabilistic character of random sampling.

It is important to understand that an increase in the sampling efficiency does not mean a decrease in the variance of the sample mean distribution. As shown in Eq. (3.24) the variance of the sample mean distribution and thus the standard error is a function of the variance of the population from which we are sampling and the size *N* of the generated random sample. As such the sampling method has no effect on the standard error.

The effect of de-clustering that was illustrated in Figure 3.15 on the distribution of the mean is represented in Figure 3.16 below.

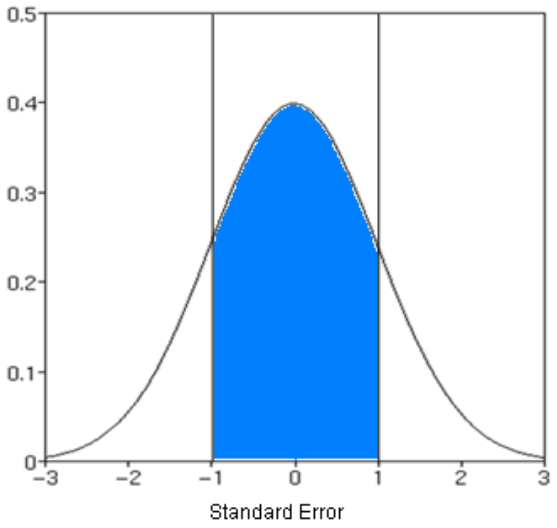


Figure 3.16: A representation of the effect of Latin Hypercube sampling on the distribution of the sample mean

Given a certain size N of the random sample and thus a certain standard error, Latin Hypercube sampling achieves a more accurate representation of the population as compared to Monte Carlo sampling by limiting the mean of the generated sample to the range closely around the actual mean as shown in Figure 3.16 above.

3.3.4.5 Simulation rules

In the previous section it was shown how the distributions of the input vector are regenerated by sampling. To account for the associations between the variables of the model one needs to determine the values of X_{11}, X_{12}, X_{13} and X_{14} in the first iteration of the function evaluated in Eq. (3.22) without affecting the randomness of the sampling. In this section it will be seen how the evaluation of the model function is tied to the correlation coefficients in the matrix without affecting the randomness of the sampling.

So as not to affect the randomness of the sampling, the sampling is split from the correlation work. This is done by adopting the Spearman's Rank Correlation Coefficient (r_s) instead of the Pearson's Correlation Coefficient (r) for correlating two variables during the simulation. The rank correlation coefficient is the same as the correlation coefficient presented in Eq. (3.13) however the rank correlation coefficient measures the association between the "rankings" of the values rather than the values themselves. In other words the rank correlation coefficient measures the association between the ranks of the x_1-x_2 values instead of the x_1-x_2 values themselves and is denoted as r_s instead of r.

In the following example the author assumes a sample of size N = 5 with a desired correlation coefficient of -0.5 between x_1 and x_2 variables. The following is a representation of the simulation procedure where the sampling is done independent of the correlations work using rank scores for the random numbers. The rank scores are randomly distributed values of varying magnitude between a minimum and a maximum. For simplicity rank scores of the form 1, 2, ..., N are used in this example.

x_1		x_2	
Random No.	Rank Score	Random No.	Rank Score
0.12	2	0.79	4
0.69	1	0.21	3
0.58	4	0.43	1
0.92	3	0.08	5
0.23	5	0.85	2

Table 3.5: Random samples of x_1 and x_2 with rank scores according to the positioning of the random numbers within the 0-1 range

First, as shown in Table 3.5 random numbers are generated without any interference. As illustrated in the previous section, each random number can be used to generate a sample value from the cumulative density function. Second, the rank scores are generated and then rearranged to give pairs of scores, which generate the desired correlation coefficient with minimum error. Thus the correlation between the rearranged rank scores as shown in Table 3.5 above is -0.5 (the desired correlation coefficient in the given example). The smallest random number is then used in the iteration with the smallest rank score; the second smallest random number is used in the iteration with the second smallest rank score, and so on. This ordering, based on ranking, continues for all random numbers, up to the point where the largest random number is used in the iteration with the largest rank score.

3.3.5 Generating the simulation results

As mentioned earlier, the Monte Carlo simulation is a sampling procedure that is used to develop a mapping from the analysis input to the analysis results. Such a mapping provides the basis for both: uncertainty analysis and sensitivity analysis. In the current project the PDF is used to provide a complete representation of the uncertainty in the result.

3.3.5.1 Uncertainty analysis

The figure below shows the total GHG emissions of the bio-hydrogen chain on a WtT basis with 50,000 iterations. The statistics of most interest in the comparative analysis are the median and the standard deviation which reflects how widely dispersed is the population.

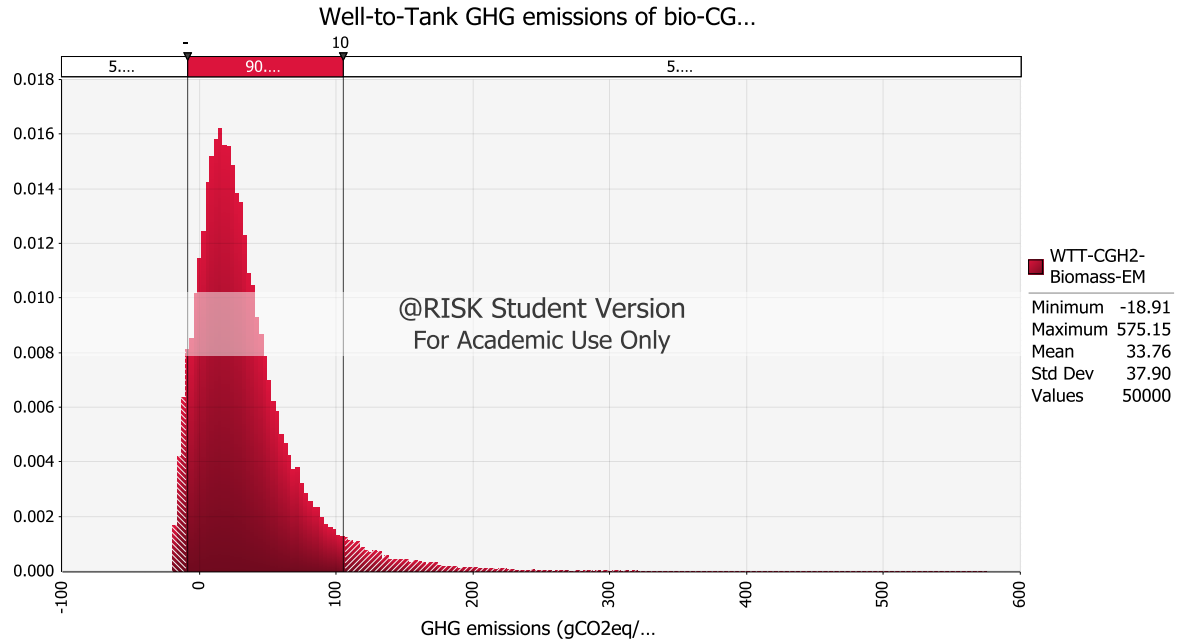


Figure 3.17: A complete representation of output uncertainty. The y-axes of all the distributions presented in this thesis represent probability density.

3.3.5.2 Sensitivity analysis

According to Saltelli *et al.* (2000) sensitivity analysis is the study about the relations between the input and the output of a model. The meaning of sensitivity analysis depends on purpose. For instance, if one want to identify variables that have significant impact on the results the "one-way" sensitivity analysis can in principle be performed were one variable is changed at a time while the other variables are constant and the effect on the result is measured on the same scale (e.g. $\pm x\%$). This type of sensitivity analysis, although not realistic because in reality different variables change simultaneously, may adequately serve the identified purpose. However, sensitivity analysis can have a different meaning and purpose. Besides the uncertainty analysis of the STM results in a comparative approach the STM is concerned with probing the output of a given chain and determining the major factors of variability across the reference models so as to investigate the disagreements in literature. This employs the sample-based sensitivity analysis using the Monte Carlo sampling technique.

The type of sensitivity analysis that meets the goal presented above focuses on questions such as "which of the input variables variances influences the model output variance most?" and "which of the input variables has to be known more accurately to reduce the output variance?" (Schwieger, November 11-13, 2004).

The scatter plot in Figure 3.18 below shows the input value sampled vs. the output result calculated in each iteration of the simulation (number of iterations is 50,000). The tightness of the clustering around a line reflects the association between the output variable and the input variable. The higher the correlation between the input and the output, the more significant is the contribution of the input to the variability of the output. In this case Figure 3.18 reflects loose clustering.

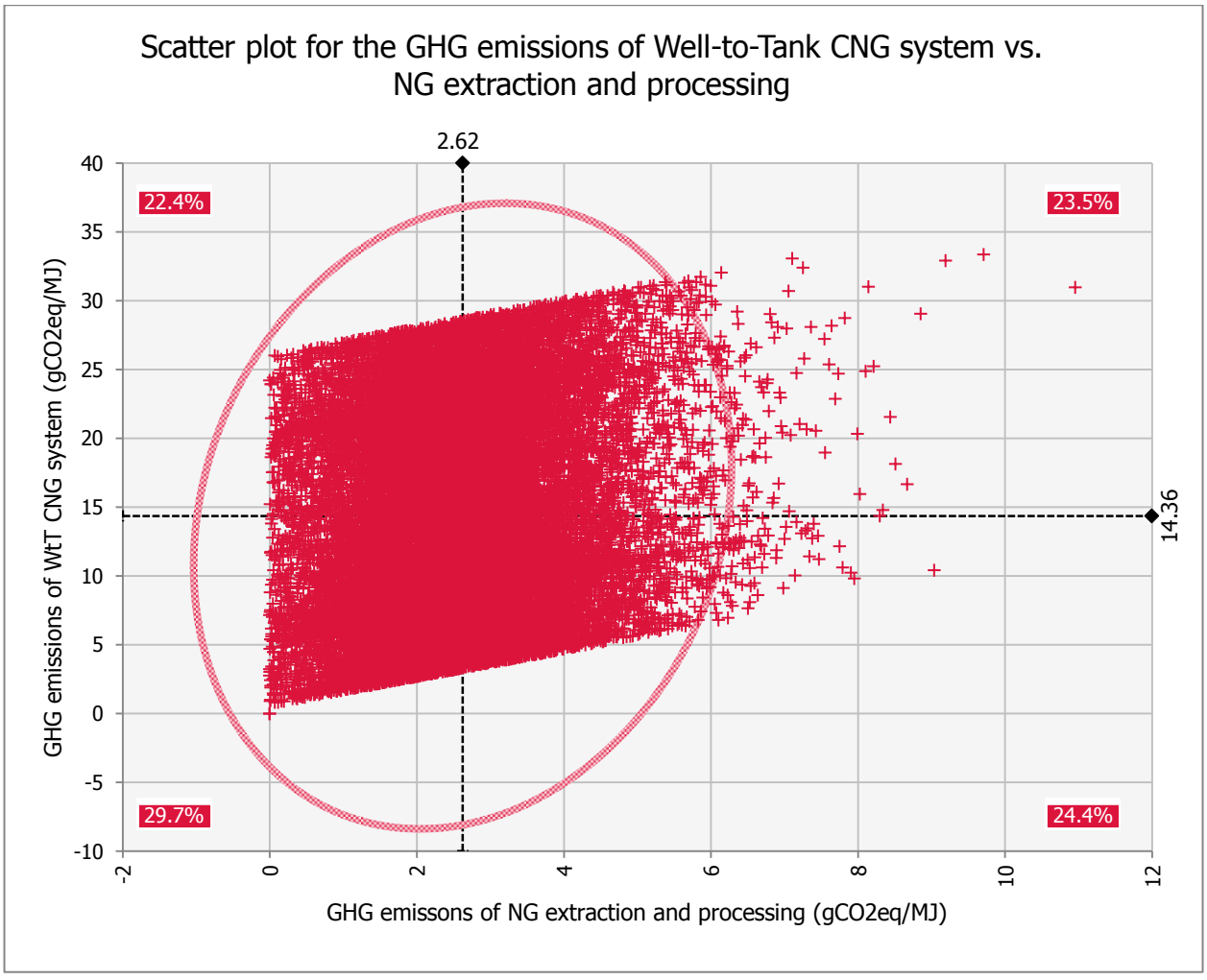


Figure 3.18: A scatter plot reflecting the correlation between the output result and the NG production process of the CNG Well-to-Tank chain

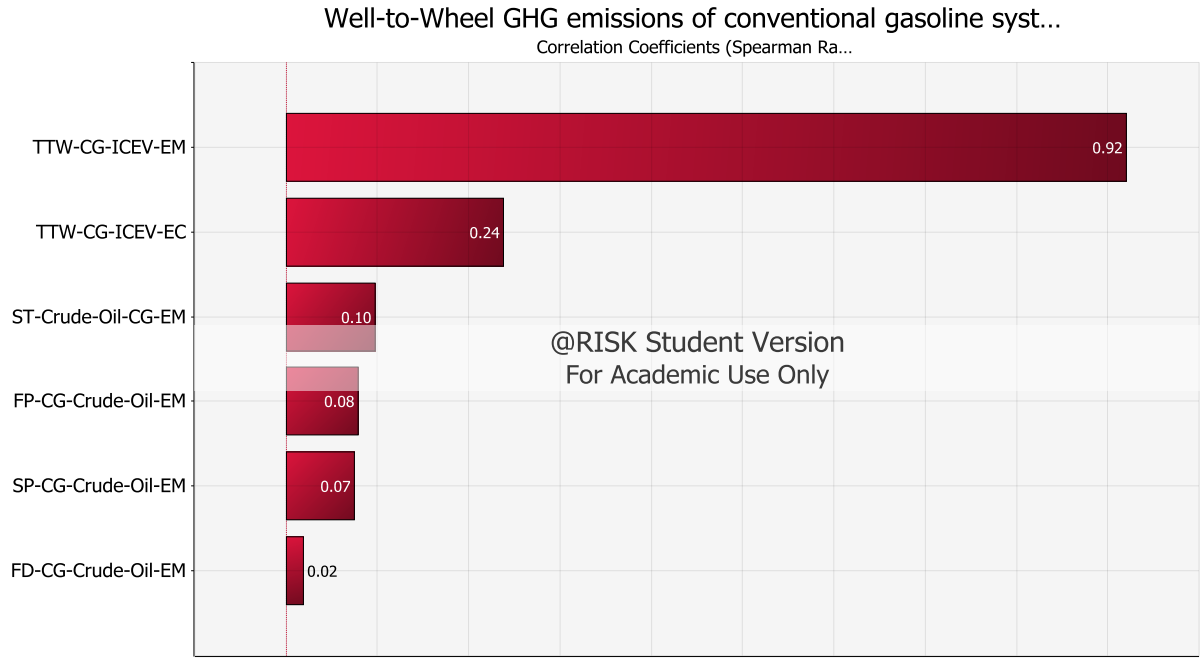


Figure 3.19: A "tornado" type chart with the longer bars at the top representing the most significant stages of the chain under study. See for nomenclature to read the abbreviations.

To display the ranking of the input distributions according to their impact on the output, the @Risk tool can be used to generate a tornado graph based on the rank correlation coefficients as shown in Figure 3.19 above. The longer bars at the top represent the input variables that are most associated with the output, i.e., the most significant stages of the chain under study.

The square of the correlation coefficient between the output and the input variables ($R_i{}^2$) is a sensitivity index that expresses the part of the variance of the model output due to the model input, and the sum of all the sensitivity indices is unity provided that the input variables of the model are independent of each other[8].

$$\sum_{i}^{M} R_i{}^2 = 1 \qquad \text{Eq. (3.25)}$$

where M refers to the number of input variables.

[8] According to Sobol (SOBOL, I. M. 1993. Sensitivity estimates for nonlinear mathematical models. *Mathematical Modeling & Computational Experiment (Engl. Transl.)*, 1**,** 407–414) only when inputs are independent the sum of all sensitivity indices is equal to 1.

As highlighted by Jacques *et al.* (2006), the problem of sensitivity analysis for a model with dependent inputs is a real one and is naturally and frequently met in practice. If inputs are correlated the sensitivity indices are not meaningful and we cannot obtain a variance decomposition of the model output. Jacques *et al.* (2006) gave the following interpretation to this: variability of two correlated variables are link by covariance, and so when we quantify sensitivity to one of these two variables, we quantify too a part of sensitivity to the other variable. And so, in the sensitivity indices of the two variables the same information is taken into account several times, and the sum of all indices is thus greatest than 1. Therefore the sensitivity analysis performed in the current project using the Monte Carlo sampling technique neglects the correlations between the input variables of the STM.

The contribution of the input variable to the variability of the output, assuming no correlations, is dependent on two factors: (i) the absolute mean of the input relative to the absolute mean of the output and thus the influence of the input on the output, and (ii) the size of the distortion from the mean which is measured by the relative standard deviation (RSD), commonly known as the coefficient of variation, as follows:

$$\sigma^* = \frac{\sigma}{|\mu|} \qquad \text{Eq. (3.26)}$$

where σ^* represents the RSD and $|\mu|$ represents the absolute mean which is calculated as follows:

$$|\mu| = \frac{1}{N}\sum_{i}^{N}|Y_i| \qquad \text{Eq. (3.27)}$$

where Y_i represents the simulation output modes and N is the number of iterations. The size of the standard deviation is measured in relative terms as a proportion of the absolute mean and not the mean. This is like having a bar of wood with half above water and half below water, the actual size of a piece of wood in relative terms is measured as a proportion of the full size of the wood bar and not the apparent size (the part above water).

Although the introduction of correlations will affect the proportion of the input variance that has an effect on the output and thus the impact of the input on the output, the purpose of the

sensitivity analysis in the current study is to roughly relate the output variability to the variability of the input variables which in turn is related to the changes in the modelling elements across the reference databases. (First a qualitative type of sensitivity analysis is performed to relate the input variance to the variation of the modelling elements which are the elements that describe the model. And second a sample based sensitivity analysis is performed to relate in quantitative terms the variability of the output to the variability of the input variables of the STM.) In other words the purpose of the sensitivity analysis in the current study is not an accurate quantitative break down of the output variance but only an approximate break down to probe the uncertainty of the output.

3.3.5.3 A possible question

This chapter was dedicated to the work on the statistics of the STM so as to ensure generation of statistically sound aggregates which provides a robust reference for decision makers in governments and the automotive industry. However, someone may question why should we go to all this trouble when we can simply create a portfolio of results from different reference models? In fact until now all of the previous attempts to compare options was done based on a portfolio of results created by compiling results from different studies into a range (IEA, 1999; MacLean and Lave, 2003b).

Such a portfolio is only a compilation of results from different studies and is not an outcome of modelling. The following example will represent the statistical shortcomings of a simple compilation of results from different studies. Let's assume a sample of different system assumptions of size $N = 5$ under each of the 5 stages that make a typical WtW STM created by reconstructing 5 WtW chains from different studies. In this case the sample space that can be generated by simulation is of size 3125, i.e., the output result would represent 3125 events and is the number of different combinations (5^5). Alternatively, without data work and simulation one can create a portfolio of WtW results of size 5 from the reference studies, i.e., an alternative portfolio of results would represent only 5 events out of the 3125 events that can be generated by the STM. Therefore the standard error of such a small portfolio with respect to the sample space under consideration is large. Not only does such a portfolio not form a statistically valid output, but even more important is the fact that with a compilation of results one cannot tease out the output uncertainty which is presented in the form of a range. In the following chapter use is made

of the bank of information that can be generated from the new type of analysis within the STM to explain the output uncertainty and highlighting any major choices that one can make to optimize the option under study.

3.4 Limitations

The language of statistical modelling is variables and correlations and not numbers as in deterministic modelling. The information embedded in the reference models is converted into mathematical functions to enable statistical analysis and the correlations define the relationships between the variables of the model. Do they move in tandem? And if so, how much do they move in tandem? However, the characterization of the collected information and the description of the relationships between the variables by correlation coefficients are not straightforward and involve some limitations.

In the main text of this chapter the limitations of characterizing input samples of size < 5 was discussed and that is because the distribution fit in such cases is not possible. However, the normal distribution was used as the default distribution and truncation was avoided unless necessary to minimize the error generated from the definition of the sample distribution. The variability of the STM output derives from the variability of the STM input and by an accurate account of the variability of the input sample one minimizes the error. Nevertheless, the number of cases where a normal distribution had to be assumed is relatively small and that is not a major limitation of the work.

The more relevant limitation comes in the description of the relationships between the variables of the STM. The correlations between the variables of the STM are estimated based on a sample of combinations of input assumptions which is not large enough to regenerate the actual relationships between the variables of the model with low standard error. One good way of managing the dependencies between the variables of a model is to avoid them where possible. However, this is not possible in the STM which is designed to combine different modelling elements. The breaking down of the STM variables to eliminate dependencies will result in losing the system aggregation and thus the whole purpose of the model. Nevertheless, work on eliminating unnecessary correlations such as the covariance due to the differences in the modelling structures as described in Chapter 2 can be done. Nevertheless, all the statistical

limitations presented above are trivial when traded for the completeness of the output aggregate which forms the backbone of the statistical validity.

4 Results Analysis and Discussion I: Sensitivity Analysis

4.1 The probing of output uncertainty

The uncertainty of the STM output stems from the differences in the modelling elements across the reference models. The output is a combination of probabilistic input assumptions each having a different level of impact. If one (i) describes the randomness of the input and (ii) determines the strength of impact of each probabilistic input assumption on the output measure by appropriate sensitivity analysis, one can probe the uncertainty of the output and point out the modelling elements that have the strongest impact. This chapter is dedicated to the analysis of the uncertainty of the input assumptions for each STM under study and the interpretation of the modelling elements that underpin the uncertainty of the output.

Before proceeding with the discussion it is noted herein that the STM is the first of its kind stochastic model which allows the probing of the output variability under discrepancies in the modelling elements including the type of elements which define different chains such as different process types (CCGT, ST), plant designs (steam co-product, electricity co-product), transport modes (pipeline, LNG via ship-ocean), feedstock types (poplar wood, corn stover), and distribution pathways (truck distribution, pipeline distribution), among others. That is achievable because the STM is designed with high flexibility having variables that can host any source of variability and combine different chains into one standard chain. The sensitivity analysis performed by the STM is not completely quantitative and includes a qualitative part which is considered first.

4.1.1 The qualitative sensitivity analysis

This is the first part of the probing process which involves relating the input uncertainty to the changes in the modelling elements across the different elements of the sample. The modelling elements as noted earlier describe the process model such as the process type, database, and time frame. To enable this type of analysis the reference databases were analysed deeply in order to map out the input samples by describing each data element; for example the transport mode, pipeline pressure, distance, pipeline gas leakage, etc for one assumption of NG transport. The full documentation of this work is presented in Appendix M. From the data map one can tease out the modelling elements that form a major source of variability. The important question here is: What are the pre-requisites of a major source of variability?

The questions of interest in this type of analysis are: "What is the *size* of the variation in the modelling element across the sample?" and "What is the *impact* of the variation in the modelling element on the input measure?" In fact, the size of the variance imposed on the input measure (e.g. the energy consumption of the electrolysis process) due to the variation in the modelling element increases with an increase in (i) the impact of the variation in the modelling element, e.g. process type, on the input measure and (ii) the size of the variation in the sample (assessed from the data map in Appendix M). Nonetheless, even if a modelling element is largely variable across the sample, the variance imposed on the input measure to the STM is not large unless the impact of the variation in the modelling element is significant. For instance, in assessing the size of the variance imposed on the energy consumption of the SMR plant from the changes in the upstream energy loss for the supply of process fuels one knows that such an effect is insignificant because whatever was the size of the variation in the upstream account the average contribution of the upstream energy loss for the supply of process fuels to the total process energy loss is insignificant and thus the sensitivity of the input measure to changes in the upstream energy loss for the supply of process fuels is insignificant. In this way one can *qualitatively* identify the major sources of variance for any input distribution to the STM.

It is important to understand that in this type of analysis one is only relating the input distribution to the variation in the modelling elements, and not measuring the actual contribution of the changes in the different modelling elements to the input distribution. In fact the superimposition of the overall effect of changes in the modelling elements on the input measure may result in obscuring each other. For instance, an increase in the energy consumption due to a change in the modelling structure may be accompanied by a decrease in the energy consumption due to a change in the conversion efficiency and thus the overall effect of changes in the modelling structure and conversion efficiency on the energy consumption obscured each other. Nevertheless, in identifying the major elements of variability one determines the assumptions, choices and/or parameters that should be targeted to eliminate the variability of the input distribution. The bank of information that can be generated from this type of analysis is very rich and can be used for many purposes not least of which include the optimization of the different systems under study as well as shedding the lights on the factors that form a source of disagreement in the WtW modelling of transport systems.

4.1.2 The quantitative sensitivity analysis

This is the second part of the probing process and represents the sampling based sensitivity analysis described in Chapter 3. The output of the STM is probed to identify the major stages (e.g. fuel production) which dominate the variability of the output. Now in determining the major stages of impact on the STM output and teasing out the modelling elements that are responsible for the variability of the assumptions in these stages, one is relating the uncertainty of the STM output to the corresponding differences in the modelling elements across the reference models.

4.2 Fuel chain (WtT)

In the following sections the different stages of the fuel chains under study are described and the uncertainty of the system assumptions is analyzed. Following the examination of Feedstock Production there are sections on Feedstock Transport, Fuel Production and Fuel Distribution. With each section, consideration is given to different types of processes.

4.2.1 Feedstock Production

This stage is where the upstream energy resource is recovered and made ready for transportation to the fuel production site. The energy resources under consideration in the present analysis are divided into three types: (a) fossil fuels which include crude oil, natural gas and coal, (b) renewable resources which include biomass, hydro, solar, wind and geothermal, and (c) uranium resources for nuclear energy.

4.2.1.1 Crude Oil

Crude oil is generally extracted under the natural pressure of the underground reservoir. In some cases it may be necessary to boost the reservoir pressure by gas injection. In most cases oil is associated with gases and must be stabilized before shipment. Water separation is also sometimes required. The associated gases used to be commonly flared but are now generally either conditioned and shipped separately (e.g. LPG) or re-injected into the reservoirs (Edwards *et al.*, 2007).

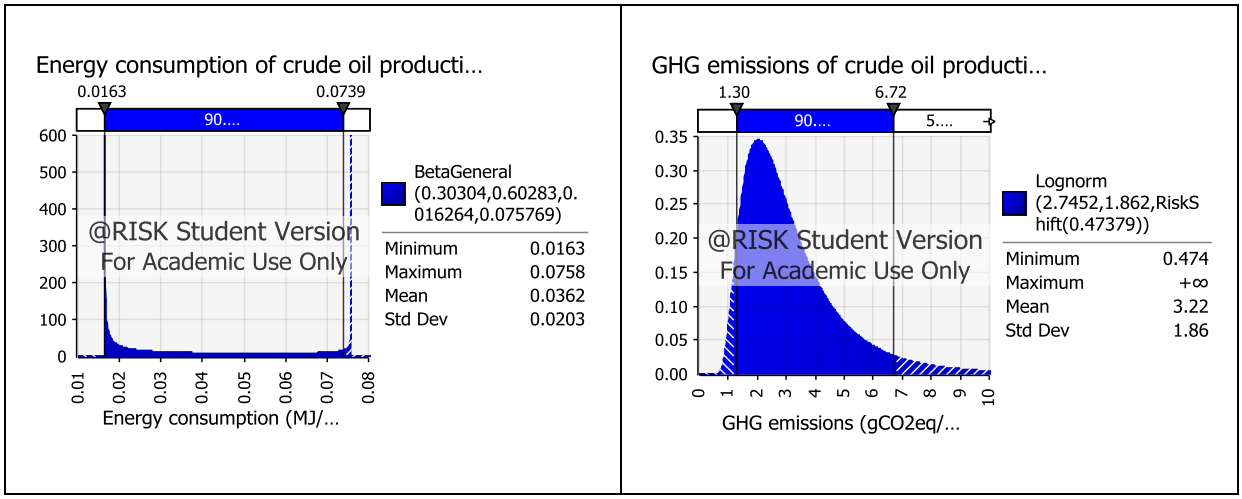


Figure 4.1: The energy consumption and GHG emissions assumptions of the crude oil production process. Note: The y-axes of all the distributions presented in this thesis represent probability density. Distribution figures of larger scale can be obtained from Appendix L after using the "swap in functions" command of @Risk software which is fully integrated into the model.

In reference to the data map presented in Appendix M the distributions in Figure 4.1 above represent the inter alia effect of an account of different models (databases and modelling structures), system boundaries, geographic locations and time frames. As one can see in the above figure the standard deviation of both the energy consumption (±0.02 MJ) and GHG emissions (±1.86 g) of the crude oil production process can have a significant effect on the reliability of the assumptions because the values of RSD[9] are ±56% and ±58%, respectively. Such an inter alia effect of variable modelling elements is most reasonably dominated by the effect of different geographic locations as production conditions vary considerably between producing regions, fields and even between individual wells. Hence it is important to account for changes in the geographic location and specific location conditions with time; the STM model offers an advantage in this respect where as seen from the data map in Appendix M it accounts for considerable changes in the geographic location including OPEC, EU, North America, Russia and developing countries. Moreover, the effect of some foreseen changes in the production conditions with time is accounted with the reference years of production ranging from 2000 to 2050.

[9] RSD = Standard deviation relative to the mean. The RSD is a standalone measure of the size of variability as depicted in Chapter 3.

4.2.1.2 Natural gas

Natural gas is produced from either dedicated fields or as associated gas in oil fields. Although it is primarily methane, the gas mixture coming out of the well can contain a range of light hydrocarbons as well as inert gases, mainly nitrogen and CO_2. Carbon dioxide produced with the bulk is not normally separated except for some fields where the CO_2 content is high. In a limited number of cases, the separated CO_2 is re-injected into the wells and this may become more common in the future. Unless this is the case, the CO_2 ends up in the atmosphere either at the processing plant or at the user site. For extraction, most of the energy is supplied directly in the form of natural gas (typically through an on-site power plant). Processing can take place near the wellhead or, as common in Russia, at a central location where light hydrocarbons can be readily used as chemical feedstock; in such a case the energy supply may be mixed and include various hydrocarbon fuels as well as electricity from the local grid (Edwards *et al.*, 2007).

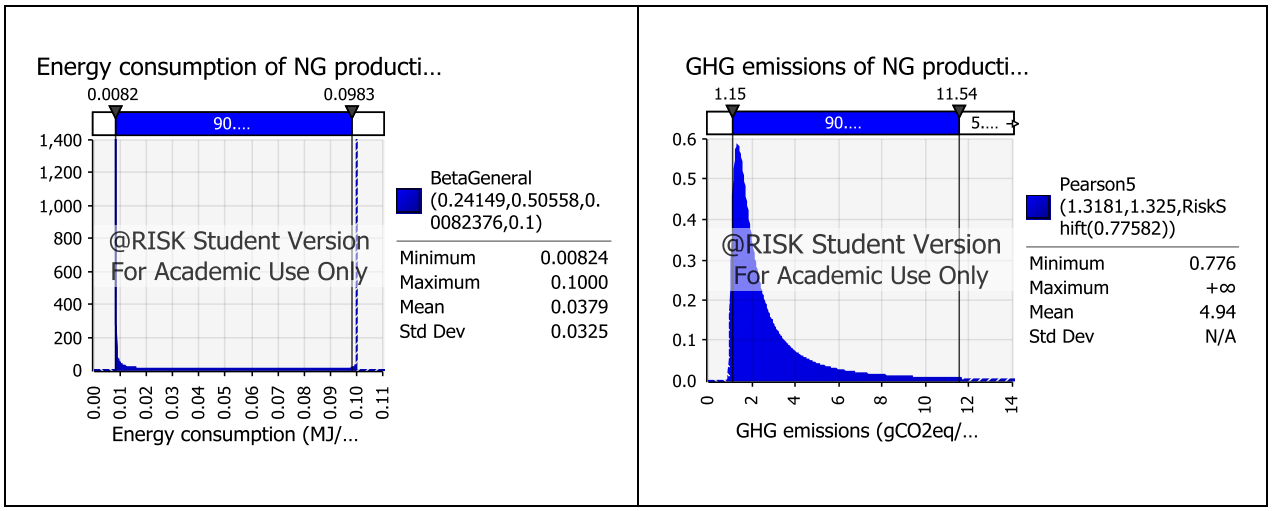


Figure 4.2: The energy consumption and GHG emissions assumptions of the natural gas production process

In reference to the data map in Appendix M the distributions in Figure 4.2 above represent the effect of an account of different models, system boundaries, geographic locations and time frames on the energy consumption and GHG emissions of the NG production process. As seen in the figure above the standard deviation of the energy consumption (±0.03 MJ) has a very significant effect on the reliability of the assumptions with an RSD of ±86%. The standard deviation of the GHG emissions is not given but the same variation is expected. This can be attributed in the first place to the energy associated with extraction and processing which varies

considerably with the producing region under different gas qualities, practices (e.g. gas flaring) and climatic conditions.

Moreover, in the case of NG production another significant element of variability is time where for example the GHG emissions from the production and processing of NG in Russia is observed to have a predicted drop from 4.20 gCO_2eq in 2010 to 2.57 gCO_2eq in 2030 (per 1 MJ of CGH2 fuel in tank produced from NG by central reforming) while all other modelling elements are constant (GEMIS of Öko-Institut, 2008). In reference to the data map in Appendix M the standardization model accounts for considerable changes in geographic location and time. The STM covers the conditions of natural gas production in the following regions: Europe (Norway, Netherlands, UK and Germany), North America, West Asia (Russia), West Siberia and North Africa (Algeria). The same changes that occur with different geographic locations, i.e. gas qualities, practices and climatic conditions, represent changes that may occur in a specific location with time. Also, the effect of some foreseen changes in the production conditions with time is accounted with the reference years of production ranging from 2010 to 2030.

It is also observed that there is an outlier assumption among the assumptions that underpin the random system assumption presented by the distribution. In observing the data set in Appendix L from which the distribution was generated one can see that the outlier assumption is that from the LCA of hydrogen production via natural gas steam reforming by NREL (Spath and Mann, 2001) which was adopted by the MIT model (Weiss *et al.*, 2000). In the NREL study the data associated with NG production were taken from the TEAM database, known as Data for Environmental Analysis and Management (DEAM); some details about the DEAM database modules can be found in the appendix of Mann and Spath (1997). It is not clear as to why the GHG emissions assumption from the NREL study is an outlier compared to the assumptions from other models. However, it is clear that the observed outlier has a considerable effect on the variance of the GHG emissions distribution as presented in Figure 4.2 above.

4.2.1.3 Coal

Coal is extracted by two main methods: (i) underground mining and (ii) surface mining. The choice of the mining method is largely determined by the geology of the coal deposit. Further details on the different methods of coal mining can be found in the comprehensive overview of coal prepared by the World Coal Institute (WCI, 2005). Coal straight from the ground, known as

run-of-mine (ROM) coal, often contains unwanted impurities such as rock and dirt and comes in a mixture of different sized fragments. However, coal users need coal of a consistent quality. The treatment of the ROM coal is often known as coal washing. The ROM treatment depends on the properties of the coal and its intended use. It may require only simple crushing or it may need to go through a complex treatment process to reduce impurities.

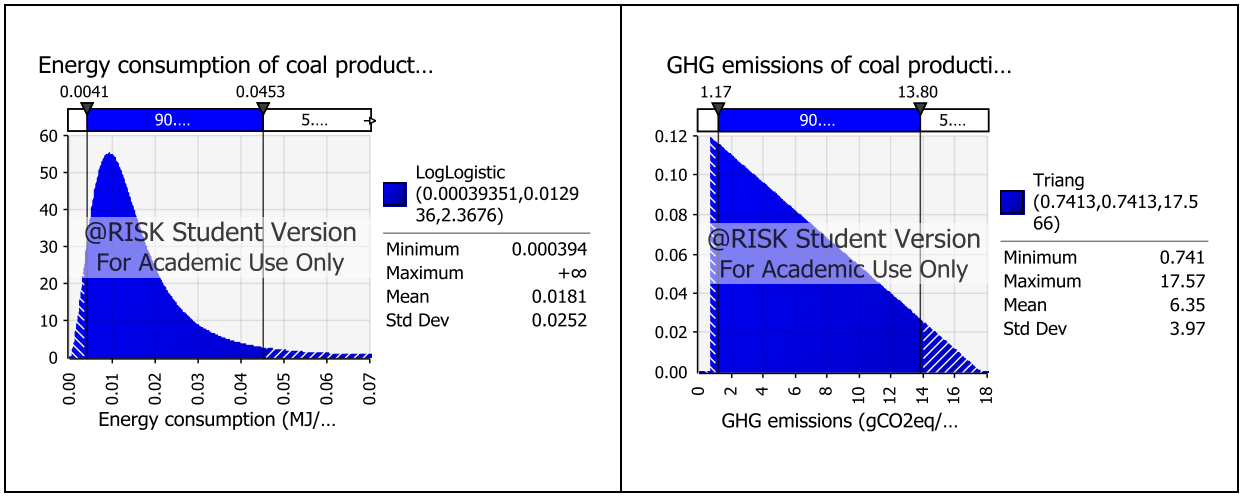


Figure 4.3: The assumptions of energy consumption and GHG emissions of the coal production process

From the figure above it is seen that the standard deviation of the distributions of energy consumption (±0.0252 MJ) and GHG emissions (±3.97 g) has a significant effect on the reliability of the assumptions with an RSD of ±139% and ±63%, respectively. In reference to the data map in Appendix M most of the data for coal production is extracted from the GEMIS model (Öko-Institut, 2008) and the distributions in Figure 4.3 mainly represent an account of different geographic locations and time frames. As mentioned earlier, the same changes that occur with different geographic locations represent changes that may occur in a specific location with time. The changes in the geographic location and time frame of coal production refers to changes in the type of coal (i.e., whether anthracite, bituminous, sub-bituminous, or lignite) and coal mining (i.e., whether deep or surface). From the distributions in Figure 4.3 above it was statistically verified that the energy consumption and GHG emissions of the production process are significantly sensitive to the inter alia effect of changes in geographic location and time. The account of different geographic locations and time frames of coal production under consideration by the STM is large including different types of coal and coal mining from Australia, North America, Russia, South Africa and Europe; the reference years of production range from 2000 to 2030. From the GEMIS model (Öko-Institut, 2008) it was observed that the direct GHG

emissions of deep coal mining in Germany drops from 11.68 gCO_2eq in 2000 to 7.66 gCO_2eq in 2020 (per MJ of coal produced); in contrast the direct GHG emissions of surface coal mining in Russia increases from 1.31 gCO_2eq in 2000 to 2.51 gCO_2eq in 2030.

As the energy consumption and GHG emissions of fossil fuel production processes are significantly sensitive to the inter alia effect of changes in geographic location and time it is important that such modelling elements should not be fixed for the unforeseen future otherwise we fail to reflect the size of the changes that may occur. This is supported by a quarterly report by EIA entitled "Carbon Dioxide Emission Factors for Coal" (Hong and Slatick, 1994) which noted that the emission factors of coal combustion fail to reflect the changing mix of coal that will occur in the future.

4.2.1.4 Biomass

The competition between the supply of biomass for fuel and the supply of food is briefly discussed. Then land use is examined for five different types of biomass. The amount of emission reductions that can be achieved through the use of biofuels in transport varies widely, depending on choices made at each stage from feedstock selection and production through to final fuel use. Although known processes can convert almost any plant material into a transportation fuel, the currently commercial options are limited to ethanol made from cornstarch or sugarcane, and biodiesel made from soybean or palm oil seeds (Peña, 2008). The biomass options under consideration for study in the present analysis include sugarcane, sugarbeet, residual biomass (corn stover, crop straw, waste wood, etc) and poplar wood. Types of biomass feedstock that directly interfere with the food supply chain such as wheat and corn were excluded from the analysis.

The current trends in the world's population growth where it is expected to grow by 40% to about 9.1 billion people by 2050 and the rapid growth in emerging and developing economies have raised concerns as to how the world will meet the projected food demand. According to agricultural and environmental experts speaking at the International Policy Council meeting in England in 2007 the global food demand will double by 2050 and increasing agricultural production will be the key to feeding the world's population (DJ, 2007). Further in the global summit in Rome in 2008 the UN chief Ban Ki-Moon told world leaders that world food production must rise by 50% by 2030 to meet increasing demand (AP, 2008).

However, the recent price surges in food commodities is not only due to demand growth but is partial due to biofuels production in advanced economies in response to higher oil prices, and, increasingly generous policy support. In fact rising corn based ethanol production accounted for about three-fourths of the increase in global corn consumption in 2006-07. This has pushed up not only corn prices but also prices of other food crops (IMF, 2008). Frederic Mousseau from Oxfam, speaking at 2008 summit in Rome, said the IMF showed that the increased demand for biofuels is contributing 15-30% to food price increases (AP, 2008). This means that while there is an urge to significantly increase the food production capacity, some food capacity is being diverted to produce biofuels which exerts *further* pressure on food supply.

The previous discussion presented enough reasoning to exclude biomass types which directly interfere with the food supply chain through the diversion of food. However, any type of cultivated biomass used as a feedstock for the production of transportation fuels indirectly interferes with the food supply chain through the diversion of land use. Thus it is not enough to look at the efficiency and global warming impact of biomass based transport chains; the synergy between food supply and energy supply and the expected competition between energy demand and food demand makes land use a top priority.

The following analysis is made to shed light on the land requirements of different types of biomass feedstock for the production of biofuels. The land use is assessed over the WtT and WtW chains and the results are listed in Table 4.1 and presented in Figure 4.4.

Type of biomass feedstock	**Land use (m^2 per gallon of ethanol)**	**Land use (m^2 per 100 km)**	**Data**
Corn	*9.78*	*31.09*	Ethanol yield[a]: 2.62 gallons per bushel of corn Corn yield[a]: 158 bushels / acre 1 acre = 0.405 hectare (ha)[b] 1 gallon of ethanol = 80.53 MJ (LHV)[a]
Wheat	*19.62*	*62.37*	Ethanol yield[c]: 3.03 t of wheat grain containing 3% H2O / t of ethanol Wheat yield[d]: 5200 kg @ 13.5% H2O / ha 17.0 MJ / kg dry wheat (LHV)[e]
Wood (poplar)	*12.98*	*41.26*	Ethanol yield[f]: 2.909 MJ of wood / 1 MJ of ethanol Wood (poplar) yield[g]: 10 t dry substance / ha 18.5 MJ / kg dry wood (LHV)[e]

Sugarcane	*6.68*	*21.24*	Ethanol yield[h]: 91.8 l of ethanol / t of sugarcane containing 72.5% H2O Sugarcane yield: 82.4 t of sugarcane / ha[h] (sugarcane H2O content 72.5%)[e] 19.6 MJ / kg dry sugarcane (LHV)[i]
Sugarbeet	*5.28*	*16.77*	Ethanol yield[j]: 0.0777 t of ethanol / t of sugarbeet containing 76.5% H2O Sugarbeet yield[k]: 68860 kg beet @ 75.0% H2O / ha 6331 MJ (LHV) / ha[l] 16.3 MJ / kg dry sugarbeet
Ligno-cellulosic residue	*0.00*	*0.00*	

[a]GREET database (ANL, 2009); [b]Oak Ridge National Laboratory, Bioenergy Conversion Factors (ORNL, 2003); [c]Punter *et al.* (2004); [d]Crop Energies, Südzucker, Cristal Union, 5 February 2008 (JRC *et al.*, 2008a); [e]Kaltschmitt and Hartmann (2001); [f]Wooley *et al.* (1999); [g]Personal communication with Murach, D., Fachhochschule Eberswalde, Eberswalde, Germany, 27 August 2003 (JRC *et al.*, 2008a); [h]Macedo (2004); [i]JEC E3 database (JRC *et al.*, 2008a); [j]JEC E3 database (JRC *et al.*, 2008a); [k]European Fertilizers Manufacturer Association (EFMA), 2008 (JRC *et al.*, 2008a); [l]JEC E3 database (JRC *et al.*, 2008a); average performance of ethanol dedicated ICE vehicle from JEC (JRC *et al.*, 2008c), GREET (ANL, 2009) and LEM (Delucchi, 2003) databases (3.2 U.S gallons of ethanol / 100 km).

Table 4.1: The land use of different types of biomass feedstock for the production of bioethanol

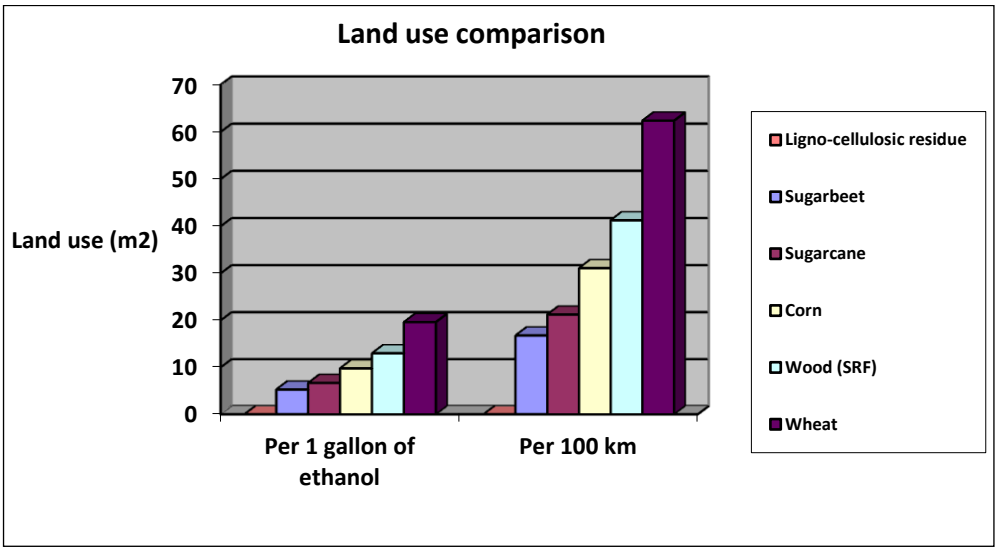


Figure 4.4: The chart of land use of different types of biomass feedstock for the production of bioethanol

The best options (excluding residual biomass) for the production of ethanol in terms of land use are sugarbeet and sugarcane (Figure 4.4). In the present analysis sugarcane from Brazil is considered as an option for study where sugarcane is imported in the form of ethanol (after

conversion); the transport of sugarcane over long distances is not feasible due to its high moisture content—72.5% of H_2O (Kaltschmitt and Hartmann, 2001). Sugarbeet was also but under consideration for study because of its relatively low land use. It forms the European alternative to imported sugar ethanol and an opportunity to build local capacity. The last option of cultivated biomass included in the present analysis is farmed wood (SRF: short-term forestry) which in terms of land use performs near to food crops such as corn, however unlike crops SRF wood forms a feedstock for alternative transportation routes through the generation of hydrogen fuel by gasification. The non-specifically cultivated types of biomass under consideration are residuals such as corn stover, wheat straw and waste wood. Such types of biomass are ligno-cellulosic residues and represent a promising option for the production of biofuels without interfering with the food supply chain.

In the following sections the author analyzes the distribution of the energy consumption and GHG emissions for the supply of these different types of biomass. Generally speaking, the stage at which most emissions occur is different for crude based and biomass based WtW chains. In the case of crude-based fuels (i.e., gasoline), most emissions occur during combustion, with fewer emissions due to production and refining/conversion processes. Secondly in the case of biofuels a carbon credit is incurred at the combustion stage that is equal to the carbon removed from the atmosphere during the growing cycle. Thus for biomass based chains nearly all the emissions occur in the fuel chain and insignificant emissions occur during combustion.

4.2.1.4.1 Sugarcane

The distributions in Figure 4.5 below represent the effect of an account of different models (databases and modelling structures), system boundaries (including the account of land use change effect), transport distances and timeframes. The standard deviation of the distribution of energy consumption (±0.03 MJ) can be attributed to the differences between the databases of different models which may assume different farming practices and amount and timing of fertilizers use. However, the variation in the distances over which the sugarcane is transported to the fermentation plant via truck (the observed variation ranges from 19 km to 100 km) is not significant. In fact cellulosic biomass (such as the cellulosic components of sugarcane) is voluminous and often has high moisture content which gives the feedstock low energy density and relatively high energy consumption during transportation (IEA, 1999). This explains the

proximity of the biomass production site to the biomass conversion site. Moreover, in contrast to the production of fossil fuels the effect of time on the supply of sugarcane is not noticeable.

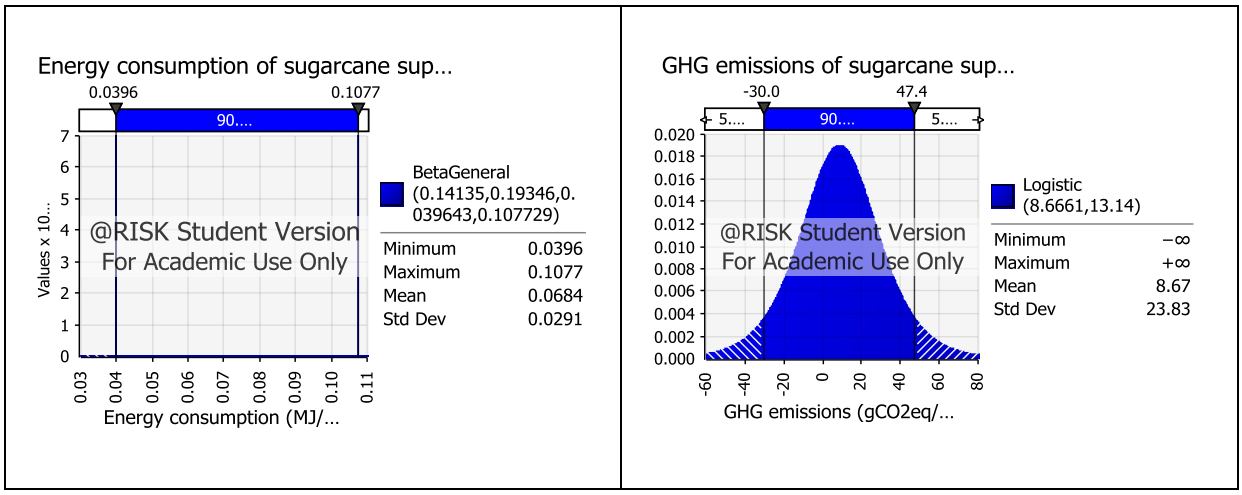


Figure 4.5: The energy consumption and GHG emissions assumptions of the sugarcane supply process

On the other hand, the standard deviation of the distribution of GHG emissions is ±23.83 g. This is partially attributed to the same factors that underpin the variance of energy consumption. Use of the data map in Appendix M without the account of land use change effect gave a range from 5.21 g to 19.42g of carbon dioxide equivalent. However the effect of changes in the amount and timing of fertilizer use on the GHG footprint is much higher than on energy consumption. Fertilizers use (specifically nitrogen use) as well as application methods determine nitrous oxide (N_2O) emissions which can be a very significant part of a biofuel GHG profile. For instance in the case of Brazil's ethanol production from sugarcane the GHG emissions from fertilizers use are 34.44% of the total, and the N_2O emissions alone form 15.21% (14.08% because of N fertilizers use), on a WtT basis[10].

Nevertheless, the dominant source of variance in the distribution of GHG emissions is the account of land use change. Recent literature has emphasized the importance of including land-use change emissions in the GHG balance of biofuels (Cherubini, 2010; Cherubini *et al.*, 2009; Gnansounou *et al.*, 2009; Peña, 2008; Fargione *et al.*, 2008; Searchinger *et al.*, 2008), however it is extremely difficult to obtain reliable estimates of emissions due to land use change which

[10] Data for the analysis of the impact of fertilizers use on the GHG profile of sugarcane is adopted from the GREET model v.1.8c database (ANL 2009. Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET). *In:* WANG, M. (ed.) Version 1.8c0 ed. Argonne, Illinois. Available: http://greet.es.anl.gov/main.)

result from direct and indirect land use changes. The direct and indirect land use changes are explained below.

a) Direct land use changes

Direct land use change occurs when production of feedstock for biofuels production displaces a prior land use (e.g. conversion of forest land to sugarcane), thereby generating possible changes to the carbon stock of the land (Gnansounou *et al.*, 2008). Generally, organic carbon is stored in three different pools: vegetation (including roots), litter (including dead wood) and soil (Cherubini, 2010). When changing land utilization, these storage pools can change until a new equilibrium is reached. Particularly important is the soil carbon pool which is very large; globally the soil carbon pool is estimated to hold 2500 Gt of carbon, compared with 560 Gt of carbon in vegetation and 760 Gt in the atmosphere (Lal, 2008). Thus even relatively small increases or decreases in the size of the soil carbon stock can be of global significance where at any one time it reflects the balance between the inputs from plant residues and other organic matter, and losses due to decomposition, erosion and leaching.

The direct land use change effect can be an advantage or a disadvantage depending on the choice of the previous state of land-use system: Converting a forest to agricultural land for biofuels production means shifting from undisturbed land of high C stock to intensive cultivation which causes severe physical disturbance to the soil and largely induces losses in the carbon stock due to the resulting decomposition, erosion and leaching. For instance the conversion of tropical moist rain forest in Brazil to sugarcane land causes a decrease of -31 t C/ ha in soil carbon stock (Hamelinck *et al.*, 2008). On the other hand, the conversion from conventional crop land to production of perennial grasses (e.g. switchgrass) where the tillage (which stimulates decomposition by physical disturbance) requirements are much lower and soil carbon inputs are increased due to greater incorporation of leaf litter and fine root material, could result in substantial build up of carbon in soil (Cherubini *et al.*, 2009).

However, the issue of carbon storage in soils is complicated by the fact that soil carbon depletion and build up are relatively slow processes, so estimating the land use change effect is difficult (Heller *et al.*, 2003). Furthermore, the changes of carbon in soil and other pools are very site specific and highly dependent on former and current agronomic practices, climate, and soil

characteristics (Larson, 2005). Thus one can see why the estimation of land use change effect is very uncertain and controversial. Nevertheless, a study conducted on agricultural land converted from conventional crop land to perennial grasses demonstrated an increase in carbon sequestration up to 1.1 t C/ha in line with expectation (Gebhart *et al.*, 1994). Other studies have also shown that perennial grasses grown for biomass feedstock production have the potential to substantially increase soil carbon levels (Lal *et al.*, 1999; Garten and Wullschleger, 2000; Conant *et al.*, 2001; Zan *et al.*, 2001; Franck *et al.*, 2004).

(b) Indirect land use changes

Indirect land use change occurs when land currently used for feed or food crops is changed into bioenergy feedstock production and the demand for the previous land use (i.e. feed, food) remains, the displaced agricultural production will move to other places where unfavourable land use change may occur (Fritsche, 2008). In other words, the direct displacement of agricultural land in location A will cause indirect displacement of land in location B. However land use generated in location B may be more intense than that in location A: "The displacement of current land-use to produce biofuels can generate more intense land-use elsewhere (Turner *et al.*, 2007)". Basically there are four ways by which one can supply a certain amount of biomass feedstock to meet a given demand of biofuels (Gnansounou *et al.*, 2008); these are listed and their possible land use change effects are elaborated:

(1) *Biomass use substitution* (i.e. diverging of biomass to biofuel production instead of food purposes): The decreasing of feedstock quantities for other purposes may eventually generate a land change somewhere else, mainly in those countries producing the impacted commodities (e.g. wheat grain).

(2) *Expansion of cultivated area:* Land used for other activity is thereby displaced and either discontinued or pushed to another location. This may increase the overall GHG emissions.

(3) *Shortening the rotation length:* The production of the alternative crops is reduced and consequently may imply a relocation of the associated activities to maintain supply. This also means more intense cultivation which is associated with decreased soil carbon stock.

(4) *Yield increment in the same land:* Increase in the yield of the biomass feedstock in the same land. In this case no indirect land use change effects incur, however, if the yield increment is achieved through increased fertilizers use this consequently results in significant increase of N_2O emissions.

c) The debate on the consideration of land use change

There is a general consensus among the LCA community that the change in land use can be expected to increase GHG emissions. However, it was seen that the estimation of direct land use change effects is very uncertain and controversial due to the difficulty of measuring changes in the soil carbon stock and the large sensitivity of the estimation to former and current agronomic practices (e.g. tillage, intensity), climatic conditions, and soil characteristics. Even more uncertain is the estimation of indirect land use change effects which is more complex. In general land use changes occur for a variety of reasons, including the need to meet rising demand for food due to rising populations and incomes. Thus, separating out land-use change emissions induced by biofuels demand is challenging and requires making a number of estimates and assumptions regarding the impacts of population and income growth, land use policies, and changes in yield and management practices on land use (Peña, 2008). In addition to estimates on how much land converts due to biofuel demand, critical assumptions include which types of lands convert for this purpose.

Although the aim is not to underestimate the GHG profile of biofuels due to not considering the land use change that may be expected to cause significant GHG emissions, the aim is also not to overestimate the GHG profile based on somewhat arbitrary assumptions. In both cases there is a high risk of drawing misleading conclusions. For instance, a recent study by Searchinger *et al.* (2008) claimed that if indirect land use change effects are quantified in relation to a hypothesized spike in US corn ethanol consumption of 56 billion litres by 2016 then the impact triggered around the rest of the world would be the release of a further 3.8 billion tonnes of carbon dioxide equivalent into the atmosphere. Clearly if the Searchinger *et al.* calculations are valid then they would constitute an indictment of biofuels policy in the US and by implication the rest of the world. The attention to such claims can be devastating if the calculations are not sufficiently robust and scientifically grounded. Actually in a critical review by Mathew and Tan (2009) the Searchinger *et al.* pronouncement was described as "bold and unqualified". With high

uncertainty in estimating the total land use change effects there is no rationale in considering default estimates to support regulatory action.

The standardization model offers a method to compromise between the different assumptions of land use change and to smooth the standing of individual estimates. Among the reference models under consideration in this work the JEC, GM-LBST and GREET models assume only modest land use changes or no land use changes at all. In contrast to a review by Gnansounou *et al.* (2009) which stated that the JEC study takes into account direct land use changes, the authors of JEC model clearly stated that the scale of the increased GHG emissions due to land use and intensification is very uncertain and controversial and therefore JEC has not included them in any of the results presented in the study (Edwards *et al.*, 2007). According to their belief the account of land use within the framework of LCA adds another level of significant complexity, uncertainty and arbitrariness. The GREET v.1.8c model, however, assumes modest land use changes by taking into account the increased emissions of direct land use changes. The following table lists default values of direct land use change emissions in the GREET model (version 1.8c):

Farmed wood	Sugarcane	Corn stover	Forest residue
-112,500 gCO_2eq/dry ton	0 gCO_2eq/tonne of sugarcane	0 gCO_2eq/dry ton	0 gCO_2eq/dry ton

Table 4.2: The direct land use change emissions of farming/collecting the biomass feedstock under consideration in the STM from GREET v.1.8c (ANL, 2009)

No further details are given regarding the assumptions that underpin the estimation of the potential land use change emissions of farmed wood cultivation (e.g. the type of land displaced), i.e. the reference study is not given. Moreover, no emissions due to land use change are included for Brazilian ethanol from sugarcane because available studies at that date had indicated that ethanol production does not induce land use changes in Brazil (Faguendes de Almeida and Bomtempo, 2007). On the other hand, the Lifecycle Emissions Model (LEM) includes a detailed methodology for the calculation of direct land use change emissions. For details on the methodology refer to Delucchi (2003, p.183-201). In the LEM model it is assumed that ultimately the alternative to any energy-biomass system is the undisturbed, native vegetation.

Nevertheless, the GEMIS v.4.5 model goes further beyond the consideration of direct land use changes and presents an approach to hedge risks of GHG emissions from indirect land use changes. The model accounts for potential GHG emissions from indirect land use changes using

a default “risk adder”. The risk adder is a global average iLUC factor derived by considering the potential GHG emissions caused by displacement to be a function of land previously used to produce food/feed in key export countries of agricultural commodities on the basis that any displacement of food/feed land around the globe will reflect the displacement occurring in the key export countries. The rationale of this assumption argues that trading countries are potentially driven to increase food/feed production to balance markets if increased feedstock production for biofuels displaces previous food/feed producing land. The key commodities considered are rape, corn, palm, soy and wheat in Brazil, European Union, Indonesia, and US. Clearly the key commodities under consideration do not include feed commodities whereas it is assumed that the derived iLUC factor equally applies to displacement of feed land (e.g. grassland). The iLUC factor is derived in terms of GHG emissions per hectare of displaced land, and discounted over the life time of the plantation program (20 years) (Fritsche, 2010). The IPCC default values (IPCC, 2006) for direct land use change were used in this work.

Apart from the major discrepancies in the GHG emissions associated with land use change, the difference between the modelling structure of the JEC model (energy in/energy out) and the modelling structures of the other reference models also forms a potential source of variability. The JEC accounts for the energy consumption and GHG emissions associated with the production and supply of those parts of the sugarcane that are used as a process fuel in the fermentation of sugarcane (i.e. bagasse) as part of the supply process. However the other reference models account for these elements as part of the sugarcane fermentation process. Although this source of variability is present, it was found to have no significant impact on the statistics of the input distributions and is not considered as one of the influencing sources of variability.

4.2.1.4.2 Sugarbeet

The sugarbeet is one of the best options in terms of land use Figure 4.4. The figure below shows the distribution of the energy consumption and GHG emissions assumptions of the sugarbeet supply system.

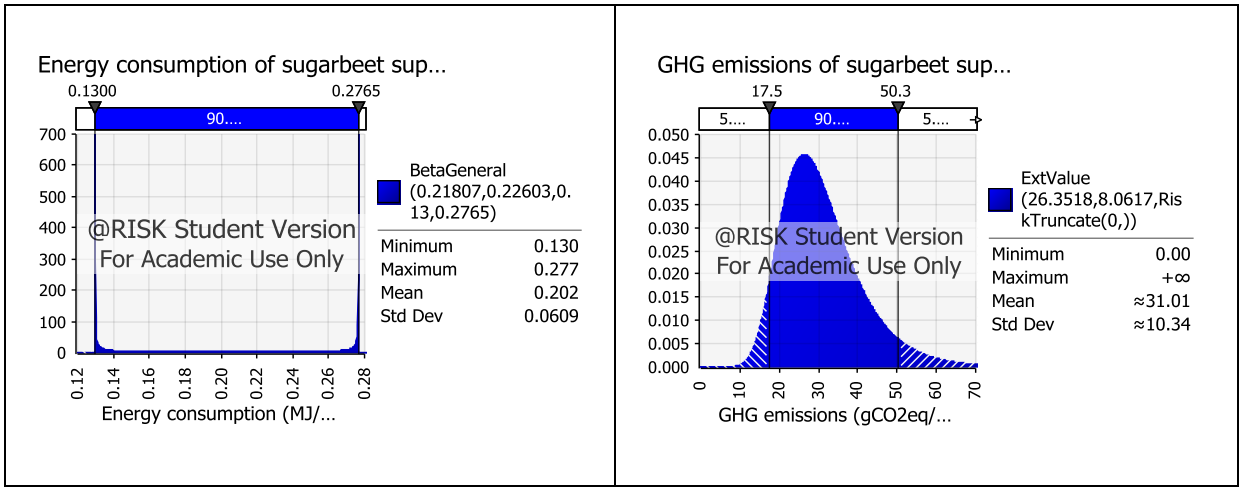


Figure 4.6: The energy consumption and GHG emissions assumptions of the sugarbeet supply process

The standard deviations of the energy consumption and GHG emissions assumptions are ±0.06 MJ and ±10.34 g, respectively; the associated RSD values are 30% and 33%, respectively. The variance is in the first place attributed to differences between the reference databases which may assume significantly different amount of fertilizers use and farming practices under different climatic conditions and soil characteristics. Moreover, the difference between the modelling structures of the reference models was found to be a considerable source of relative variability[11]. The JEC and GM-LBST models account for the upstream effects of those sugarbeet components that are used as a process fuel (i.e. pulp) within the profile of the sugarbeet supply process, whereas the GEMIS and GHGenius (Canadianized version of LEM) models account for the upstream effects of the sugarbeet components used as a process fuel within the profile of the fermentation process. Nevertheless the variance of the GHG emissions does not reflect a strong variability across the reference models due to the assumption of land use change. In fact, GHG emissions associated with direct land use change is only taken into account by the Canadized version of the LEM model (GHGenius), whereas the rest of the reference models including GEMIS agree on not assuming land use change associated with the supply of sugarbeet. The limited consideration of land use change across the reference models for sugarbeet explains to some extend the lower variance of GHG emissions (±10. 34 g) compared to that associated with the supply of sugarcane (±23.83 g).

[11] Mention is made to relative variability as RSD is low.

4.2.1.4.3 Farmed wood

As seen in Figure 4.4 short-rotation wood performs near to crops such as corn in terms of land use per U.S. gallon of ethanol and has the advantage, like other food crops (e.g. perennial grasses) in not generating a direct competition between the demand for food and the demand for biofuels. Such types of non-food crops indirectly compete with food for land and water use; hence the impact on food markets can be avoided in the medium-run by growing on degraded and idle land. Moreover, as depicted in Table 4.2 the land use change associated with the short-rotation farming of wood can potentially increase the soil carbon stock giving rise to carbon sequestration.

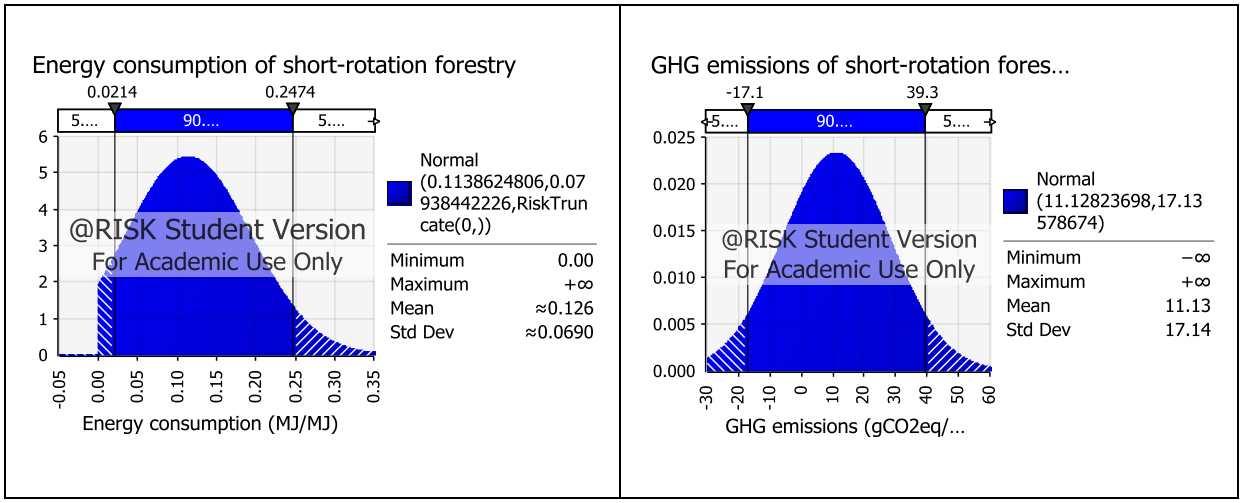


Figure 4.7: The energy consumption and GHG emissions assumptions of the short-rotation forestry supply process

According to Peña (2008) the production of farmed wood as compared to conventional crops requires lower fertilizers input and reduced tillage which also implies lower energy consumption, lower N_2O emissions from fertilizers use, and lower costs. However, from the data map in Appendix M the distributions in Figure 4.7 are obtained. These represent the effect of different models (databases and modelling structures), system boundaries (including the account of land use change), and various transport scenarios. The standard deviation of the energy consumption and GHG emissions was found to be ±0.07 MJ and ±12.41 g, respectively. The effect of the standard deviation of the energy consumption on reliability is significant given an RSD of ±55%. This makes it difficult to agree or disagree with the observations of Peña (2008) quoted above.

In line with the production of other types of cultivated biomass a primary source of variance is the differences between the reference databases with respect to significantly different

assumptions on the amount of fertilizers use and farming practices (e.g. tillage). As mentioned earlier the effect of discrepancies in the amount and application of fertilizers use has a much higher effect on the GHG emissions. For instance, the assumption of field N_2O emissions in the GREET and JEC models are 0.00083 g(N_2O) and 0.0025 g(N_2O) per 1 Mega Joule of wood produced, respectively, which reflects a strong variation in the assumed amount of fertilizers used. A second but smaller source of variability is the differences in the energy consumption and GHG emissions associated with the pre-treatment (chipping) and transportation of wood to the fermentation plant. On the other hand, the assumptions on land use change are not found to be a major source of variability because all of the reference models except for GREET did not include land use change for the short-rotation farming of wood. However, the consideration of direct land use change by GREET affected the variance on GHG emissions and explains the negative spread in the associated distribution.

The variance presented above is to a considerable extent an effect of different modelling structures. The JEC and GM-LBST models account for the energy consumption and GHG emissions associated with the supply of the farmed wood components used as process fuel within the profile of the wood supply process, the GREET model accounts for this in the profile of the wood fermentation system. This explains to some extent the significantly smaller energy consumption assumed by GREET (0.032 MJ) as compared to the JEC and GM-LBST databases which assume an energy consumption of 0.12 MJ and 0.19 MJ, respectively.

4.2.1.4.4 Residual lingo-cellulosic biomass

The ethanol from residual biomass pathway does not use land and therefore is among the most promising pathways for the prevention of competition with food for land and fresh water. Efforts to commercialize cellulosic biomass conversion processes (including the conversion of non-food crops such as short rotation forestry) focus on developing enzymes capable of breaking cellulose down (enzymatic hydrolysis) for fermentation; as well as the gasification of cellulosic woody biomass in alternative pathways that generate hydrogen fuel for transportation. Further the production of residual biomass (e.g. wheat straw) does not induce significant land use changes and promises a low GHG profile. In addition such a raw material is diverse, widespread, relatively cheap and easily available and thus is viewed as the ideal choice for the production of biofuels.

The production of biomass residues is a natural result of current economic activity and are produced irrespective of the demand for biofuels. However, the ongoing debate on the actual possibilities of crop residue removal from agricultural systems for bioenergy production stems from the potential effects of crop residues removal and whether one should remove crop residues from the field or plough them back to maintain soil quality and crop yield. For instance the removal of straw may decrease the wheat grain productivity because of lower net mineralization of N in soils (Gabrielle and Gagnaire, 2008). This is compensated by increased application of synthetic fertilizers to minimize the decrease of grain yield. Moreover, the removal of straw may decrease the soil carbon stock and contribute to increased net carbon emissions by decreasing the annual increase in soil carbon stock which would occur by not removing the straw (Cherubini, 2010; Cherubini *et al.*, 2009). On the other hand, the removal of straw slightly decreases N_2O emissions because the return of straw to soil increases soil's denitrification potentials and its capacity to produce N_2O (Cai *et al.*, 2001). This contributes to offsetting the increased N_2O emissions from the increased application of fertilizers to maintain the crop yield. On balance a recent LCA concluded that the removal of wheat straw had limited consequences on field emissions (Gabrielle and Gagnaire, 2008).

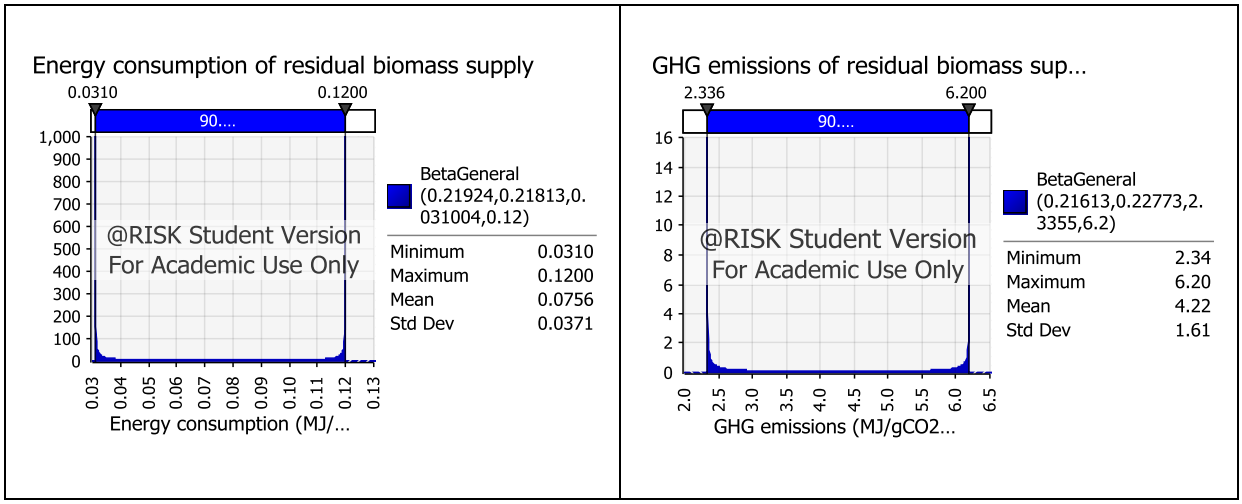


Figure 4.8: The energy consumption and GHG emissions assumptions of the residual ligno-cellulosic biomass supply process

Using the data map in Appendix M the distributions in Figure 4.8 were obtained taking into account different models (databases and model structures), various residual biomass types (straw, stover and waste wood), different transport scenarios and distances, system boundaries, and time frames. The standard deviation of the energy consumption and GHG emissions

assumptions of the residual biomass supply system were found to be ±0.04 MJ and ±1.61 g, respectively. The variance of the GHG emissions is small compared to that of the GHG emissions associated with the supply of other types of biomass due to the absence of land use change. Indeed all the reference models assume no land use change associated with the collection of residual biomass including forest residues. This level of land use change is believed to be negligible and can be ignored.

The observed variance in the energy consumption and GHG emissions, is attributed in the first place to variation in the assumptions of additional fertilizers use and the pre-treatment energy consumption (this includes the natural gas and electricity used to dry crops or chop residual wood) which differs with the different types of residual biomass. Here it is noted that all the energy consumption and GHG emissions from crop farming are attributed to the grains and not to the straw or stover. However, the energy consumption and GHG emissions associated with maintaining the crop yield after the removal of crop residues is attributed to the crop residues. The additional fertilizers use associated with the collection of crop residues is taken into account in GREET, JEC and GM-LBST models, whereas the GEMIS model does not account for the additional fertilizers use due to the focus upon the collection of ligno straw from agriculture. In fact the GEMIS model only accounts for the collection and delivery of straw to the edge of the field. On the other hand, forest residue/waste wood is not an agricultural residue and thus its collection does not imply additional use of fertilizers use but the production of waste wood does require energy for pre-treatment (chipping).

The difference between the modelling structures of the reference models is also a considerable source of variability; this factor of variability was described in the previous sections. Finally it is noted that there is considerable variation in the transport of residual biomass from the edge of the field to the fermentation plant. The various scenarios include truck transport over a distance from 48 km to 100 km, and truck transport over a distance of 50 km followed by inland navigation by bulk carrier over a distance of 400 km.

4.2.1.4.5 Biomass for hydrogen fuel

As noted earlier, ligno cellulosic biomass can be used as feedstock in alternative pathways such as gasification to generate hydrogen fuel. An option under study in the current standardization is residual biomass supplemented by non-food crops such as perennial grasses and short-rotation

crops for the generation of hydrogen fuel via gasification. The following distributions represent the variation of the energy consumption and GHG emissions assumptions of the supply of cellulosic biomass including short-rotation forestry to gasification plants of variable sizes. The strategic question in this analysis is how does hydrogen from cellulosic biomass compare with ethanol from different types of biomass?

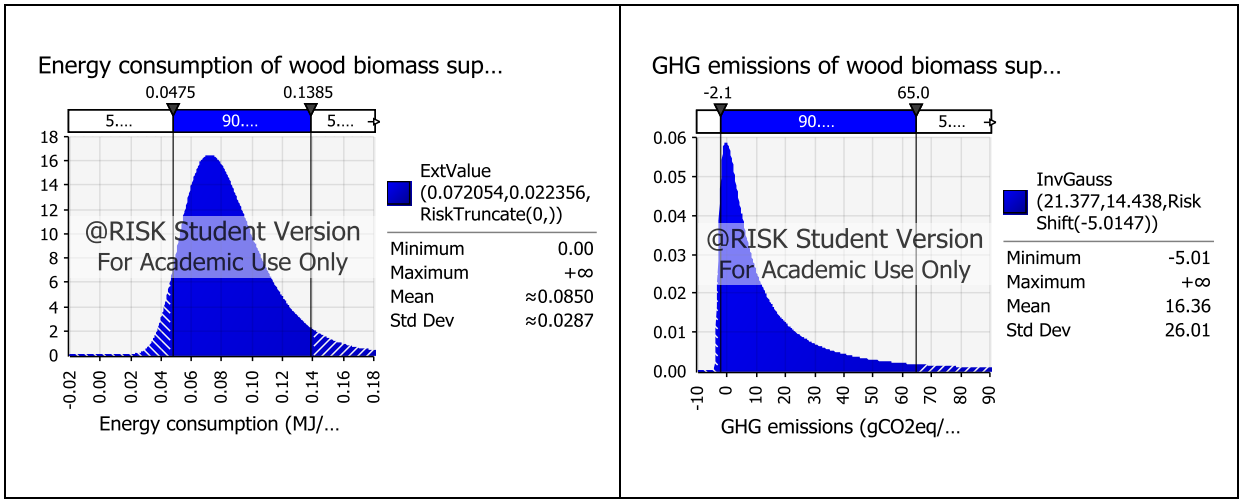


Figure 4.9: The energy consumption and GHG emissions assumptions of the wood-biomass supply process

The distributions in Figure 4.9 summarize the data map in Appendix M and represent the combined effect of inter alia different models (databases and model structures), types of wood feedstock (waste or farmed), transport scenarios and distances, system boundaries (including the account of land use change), and time frames. The standard deviation of the energy consumption and GHG emissions for the wood supply system is ±0.03 MJ and ±26.01 g, respectively. The variance of the energy consumption mainly derives from variations in the assumptions of the fertilizers use across different types of wood (waste or farmed) and has a small RSD. The collection of waste wood does not imply the use of additional fertilizers, whereas short-rotation forestry does and the amount varies from one database to another depending on the reference soil type, climatic conditions and crop management. Secondly there is considerable variation in the transport of wood after pre-treatment (chipping) to the gasification plant. The scenarios of wood transport include truck transport over a distance from 12 km to 121 km and truck transport over a distance of 50 km followed by inland navigation by bulk carrier over a distance of 400 km.

Thirdly the difference between the modelling structures of the reference models also present a source of variability. The upstream of the wood used as a process fuel in the fermentation process is accounted by some models (e.g. JEC) within the profile of the supply process, whereas

other models (e.g. GEMIS) accounts for the supply of wood used as a process fuel within the profile of the fermentation process.

Interestingly the variance of the GHG emissions assumption predominantly derives from the differences in the assumptions of land use change. Again this highlights that land use changes is a major source of uncertainty.

4.2.1.5 No-biomass renewable resources

Renewable energy resources are immense and their natural flows through the earth's ecosystem exceeds the current energy use (approximately 425 EJ[12] in 2002 (Johansson *et al.*, 2004)) by many times. Examining possible implementation and growth rates for different technologies, a 2004 report from the European Renewable Energy Council concluded that renewable energy could meet base-load power needs, and in fact, could provide 50% of the world's primary energy by 2040 (EREC, 2004). Similar studies from Shell Oil have explored scenarios in which one third to one half of the world's energy can come from renewables by 2050 (SI, 2001).

Renewable Resource	**Technical Potential (EJ/yr)**	**Theoretical Potential (EJ/yr)**
Hydropower	50	150
Biomass energy	>250	2900
Solar energy	>1600	3,900,000
Wind energy	600	6000
Geothermal energy	5000	140,000,000

Table 4.3: Renewable resources potential (Goldemberg, 2000)

As apparent in Table 4.3, recoverable renewable resources exceeds the world's energy use by millions, however, an analysis based on recoverable resources is irrelevant because hydrocarbon occurrences or natural flows become resources only if there is demand for them and appropriate technology has been developed for their conversion and use. The appraisal of technical potential therefore takes into account engineering and technological criteria. The picture is clear: the potential of what renewable resources can produce is immense in comparison with global energy use.

[12] 1 Exa Joule (EJ) = 10^6 TJ = 10^{18} J.

Does this mean that renewable energy resources are infinite? Despite the unlimited potential of renewable energy sources, there are a number of factors that constrain its realization. For instance, although the potential of wind energy is immense, the number of sites suitable for the development of major wind farms that are acceptable to the society is limited. As such, renewable resources in practice are finite sources of energy and their utilization is subject to the laws of physics; hence the efficiency of renewable energy pathways is as important, if not more important, than the efficiency of fossil-based pathways. Renewable resources are the ultimate source of energy and the present study is, in part, dedicated to the analysis of potential renewable energy-based pathways to uncover the most efficient way of utilizing such valuable resources.

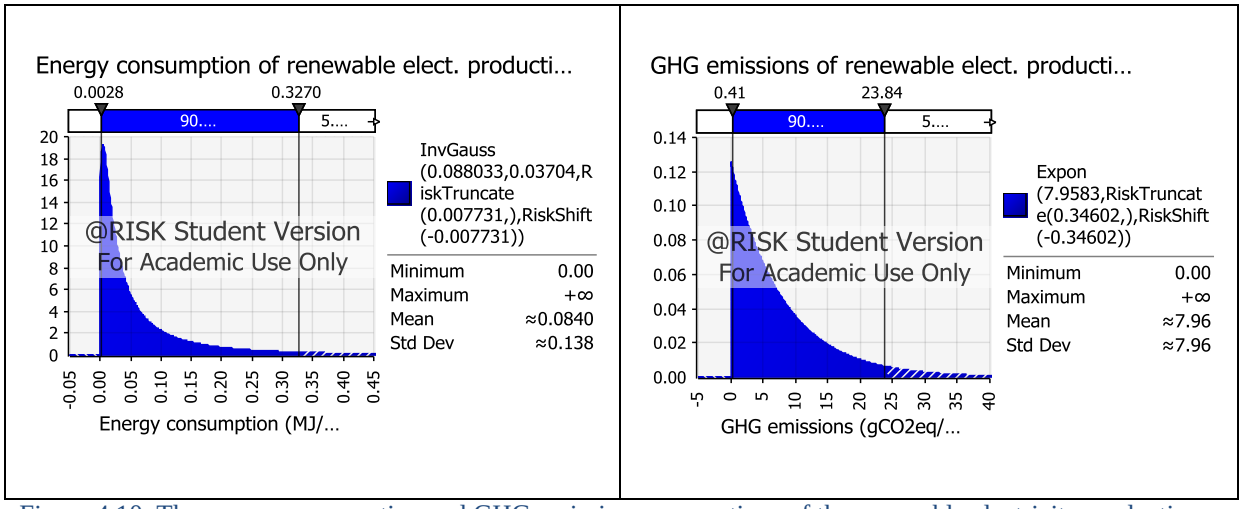


Figure 4.10: The energy consumption and GHG emissions assumptions of the renewable electricity production process

From the data map in Appendix M the distributions in Figure 4.10 were obtained to represent inter alia an account of mainly different types and sizes of renewable technologies, system boundaries and time frames. As shown in Figure 4.10 the standard deviation of energy consumption (±0.14 MJ) and GHG emissions (±7.96) is very large and significant given RSD of ±164% and ±100%, respectively.

In the following analysis the author will investigate the significance of accounting for the energy consumption and GHG emissions associated with the manufacturing of production systems for biomass and fossil fuels and compare them with those for renewable electricity production. The table below depicts the energy consumption and GHG emissions associated with the production of renewable and non-renewable resources, with and without the inclusion of the system for manufacture within the boundaries of the LCA.

Production system (reference year)	Energy consumption ($MJ/MJ_{feedstock}$)			GHG emissions ($gCO_2eq/MJ_{feedstock}$)		
	w/ construction	w/o construction	Difference	w/ construction	w/o construction	Difference
PV multi crystal modules including aluminium frame and rack (2010)	0.445	0.000	**0.445**	29.3	0.0	**29.3**
Big wind farm, 10 units,1800 kWh each, excluding cables and transformers (2010)	0.048	0.000	**0.048**	6.6	0.0	**6.6**
Run of the river big hydro dam (2000)	0.061	0.000	**0.061**	11.0	0.0	**11.0**
Geothermal steam turbine w/ auxiliary electricity for operation (2005)	0.452	0.431	**0.021**	29.2	26.8	**2.4**
OPEC onshore secondary crude oil extraction (2010)	0.023	0.021	**0.002**	3.2	2.9	**0.3**
South Africa deep coal extraction (2010)	0.012	0.011	**0.001**	9.9	9.8	**0.1**

Table 4.4: Energy consumption and GHG emissions associated with the manufacturing of renewable and non-renewable feedstock production processes. Source: GEMIS v.4.5 (Öko-Institut, 2008)

As shown in Table 4.4 the energy consumption and GHG emissions associated with the manufacture of renewable electricity production systems can be very significant spreading over a range of 0.021 – 0.445 MJ and 2.4 – 29.3 gCO_2eq, respectively, per Mega Joule of feedstock produced. On the contrary the energy consumption and GHG emissions associated with the manufacturing of non-renewable feedstock such as crude oil and coal is insignificant spreading over a very narrow range of 0.001 – 0.002 MJ and 0.1 – 0.3 gCO_2eq, respectively, per Mega Joule of feedstock produced. This explains why the inclusion of system manufacturing/construction within the boundaries of the LCA was previously not considered to be necessary. However the situation is completely different with regard to manufacturing of renewable electricity.

The difference between the system boundaries of the reference models with regards to the inclusion of system manufacturing/construction is a major source of the variance presented in Figure 4.10. Most of the reference models including GREET, JEC and GM-LBST assume that electricity from renewables such as wind, hydro and solar is created from nothing and thus the generation of electricity from renewable resources is 100% efficient. This assumption stems from the fact that drawing up the energy balance of renewable energy resources presents a specific problem as the input energy (e.g. solar) cannot be precisely defined and is, for all practical purposes, unlimited. However, assumptions from such models are simplistic and fail to consider the energy consumption and GHG emissions associated with the manufacturing of the system. As depicted in Table 4.4 and noted in the above paragraph the account of energy

consumption and GHG emissions associated with the manufacturing of renewable electricity generation processes can be very significant. On the other hand, the GEMIS model takes into the LCA account the energy consumption and GHG emissions associated with the construction of the system. The account of energy consumption and GHG emissions associated with the manufacturing of different renewable electricity generation systems is highly variable depending on the system type and size. Most noticeable is the high energy consumption and GHG emissions associated with the construction of photo-voltaic (PV) multi-framed crystal modules of area of 21.65 m^2. It is also noticeable that the geothermal system is not truly renewable requiring significant amount of auxiliary electricity for operation. The latter factor causes a large deviation from the mean and increases the variance of the distributions.

4.2.1.6 Uranium

The production of uranium fuel for electricity generation consists of mining/milling uranium ores, fuel conversion, enrichment and fabrication. This is briefly described by Fthenakis and Kim (2007) as follows. (i) Uranium ore is mined either at the surface or underground, crushed, ground into a fine slurry (milling), and then leached with sulphuric acid. Uranium is then recovered from solution and concentrated to solid uranium oxide (U_3O_8) which is often called yellow cake. (ii) Uranium (U_3O_8) is converted into hexafluoride (UF_6) and heated; the UF_6 vapour is then loaded into cylinders where it is cooled and condensed to a solid. (iii) U235 is separated from U238 and subsequently enriched either by gaseous diffusion or by gas centrifuge. (iv) Enriched UF_6 is converted to fuel (UO_2) powder and shaped into small pellets that are stacked inside thin fuel rods made of a zirconium alloy or stainless steel; they are then sealed and assembled into fuel assemblies. This final stage is the fuel rod fabrication.

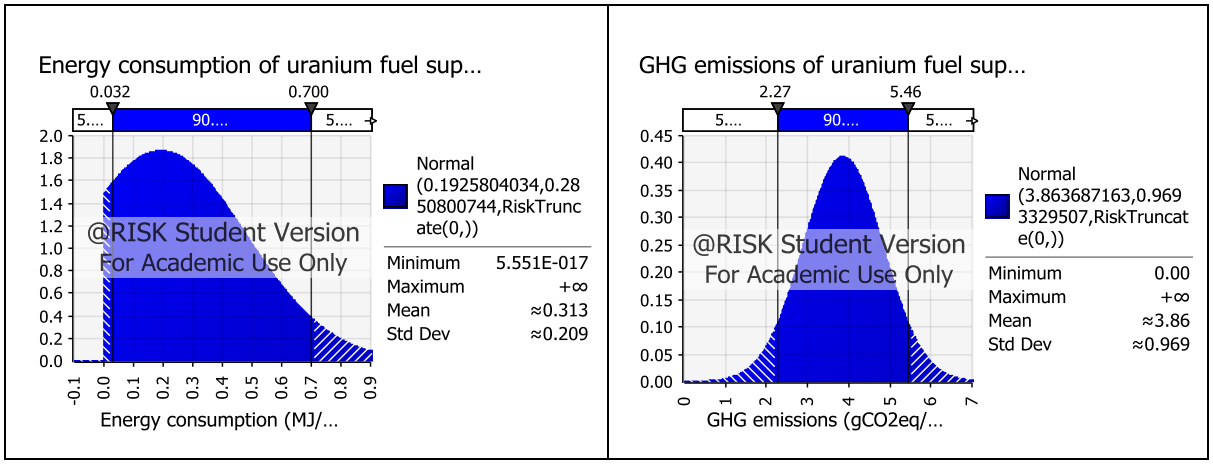


Figure 4.11: The energy consumption and GHG emissions assumptions of the uranium supply process

The uranium fuel supply stage of the STM includes the transport of uranium in the form of ore or else in the form of solid UF_6. Interestingly from the data samples in Appendix L one can note the large discrepancy for the energy consumption between the JEC assumption (0.62 $MJ/MJ_{electricity}$) and the assumptions of GEMIS (0.038 $MJ/MJ_{electricity}$) and GREET (0.057 $MJ/MJ_{electricity}$) even though the JEC model adopts the input data for the modelling of the uranium production from the GEMIS database (version 4.1.3.2) as quoted in the JEC input data excel sheets (JRC *et al.*, 2008a). This sharp discrepancy forms the major source of variability in the energy consumption observed in Figure 4.11 above. Upon probing the assumptions of the different databases it was found that the major difference between these databases in the production of uranium is the assumption of the uranium loss in the UF_6 production process. From the GEMIS database, one can find that the US, ZA (South African) and DE (German) UF_6 production processes are assumed to involve no uranium losses whereas the FR (French) UF_6 production process is assumed to involve a loss of 10% of the fissionable input (U235). The GEMIS assumption quoted above assumes the German case whereas the JEC model adopts the French case from the GEMIS database.

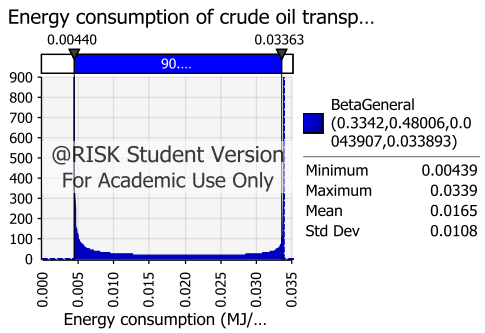
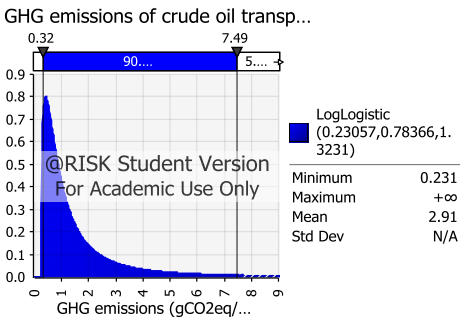
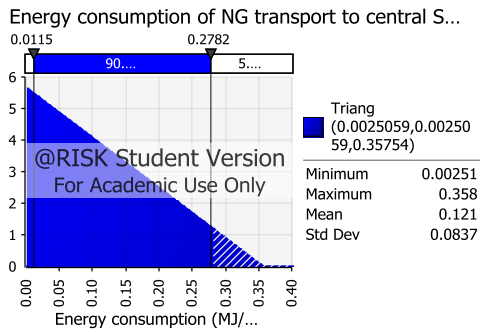
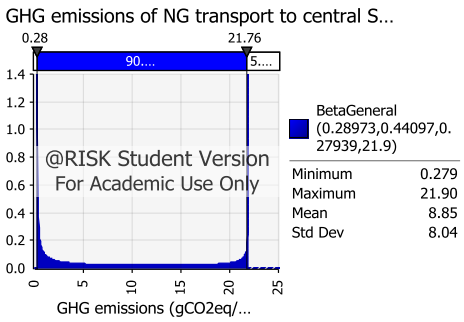
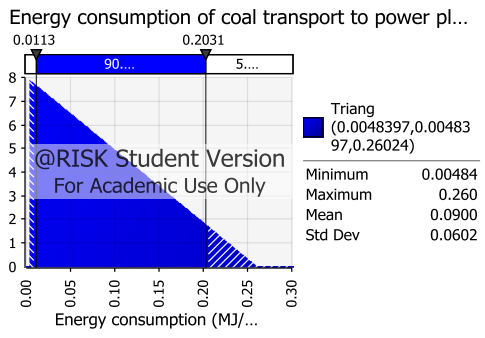
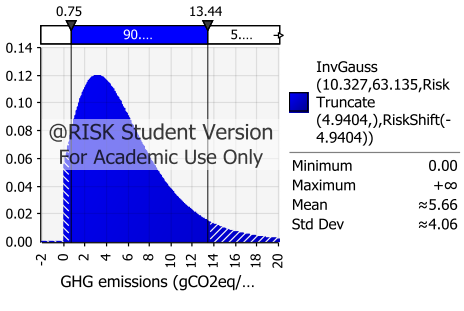
In terms of the GHG emissions the picture is different as the variance has only a quiet impact on the reliability of the assumption (RSD = ±24%). The variability of the GHG emissions is primarily attributable to the differences in the modelling structures.

4.2.2 Feedstock transport

The following table depicts the distributions of the energy consumption and GHG emissions associated with the transport of the different types of feedstock under consideration in the present

study. This excludes the biomass and uranium feedstock for which the transport is part of the feedstock supply stage in the STM.

Table 4.5: The energy consumption and GHG emissions of transport of different types of feedstock

	Energy Consumption (MJ/MJ_{Fuel})	GHG Emissions (gCO_2eq/MJ_{Fuel})
Crude oil transport		
NG transport		
Coal transport		

The variability of the transport of different types of feedstock is generally attributable to the transport distance. Crude oil, the raw material for gasoline, moves either by pipeline or by sea in large tankers. The energy consumption and GHG emissions parameters for the transport of crude oil to the refinery site is tied to the distance between the extraction site and refinery. Domestically produced crude or crudes extracted near centres of consumption have a clear advantage over imported crude oil. The distances under consideration in the STM include 1000 km pipeline for domestic crude, >5000 km pipeline for long distance imports, and far distance

via ocean tanker plus 500 km of pipeline distribution for overseas crude. The range of distances under consideration in the STM is representative of most of the crude oil transport distances assumed across the World depending on the domestic to non-domestic crude supply ratios and the different distances from extraction sites to local refineries.

Natural gas at a proximate distance from the consumption site is transported via pipeline. Alternatively, natural gas at a far distance is processed into LNG and shipped via ocean tanker to the destination terminal where it is vaporized and distributed by pipeline to the consumption site, or else distributed from the destination terminal via truck tanker in the form of LNG and vaporized/compressed at the consumption site. The reference models of the STM assume different supply options and transport distances based on the specific geographic scope of the study. The distances under consideration in the STM include short distance pipeline for domestic NG (~250 km), long distance pipeline for imported NG (850, 11500, 1950, 4500, 5250 and 7500 km), and far distance through LNG via ocean tanker.

Coal is generally transported by conveyor or truck over short distances. Trains and barges are used for longer distances within domestic markets. Ships (ocean) are commonly used for international transportation. The distances under consideration in the STM include 250 to 700 km via train (inland) plus 250 to 530 km via ship (inland), and 100% train (inland) over a distance of 500 to 1000 km for domestic coal, distribution to rail terminal plus train (outland) transport over a distance of 6000 km for long distance imports, and distribution to sea terminal for shipping over distances of 8000, 15000 and 21000 km for far distance imports.

4.2.3 Fuel production

The fuel production stages under study in the present standardization include the refining of crude oil to gasoline, the electrolysis of water to hydrogen, the fermentation of biomass to ethanol, the gasification of biomass to hydrogen, the reforming of natural gas to hydrogen, and the generation of electricity from natural gas, coal and uranium. In most of the pathways under study, the fuel production stage is the most energy intensive stage. Hence, the development of the Well-to-Wheels efficiency hinges on the improvement of the feedstock conversion efficiency.

4.2.3.1 Crude refining

An oil refinery is a complex combination of process plants, the objective of which is to turn crude into marketable products of the right quality and in the right quantities. This includes physical separation of the crude components, treatment to remove such compounds as sulphur, and conversion of mainly heavy molecules into lighter ones (Edwards *et al.*, 2007).

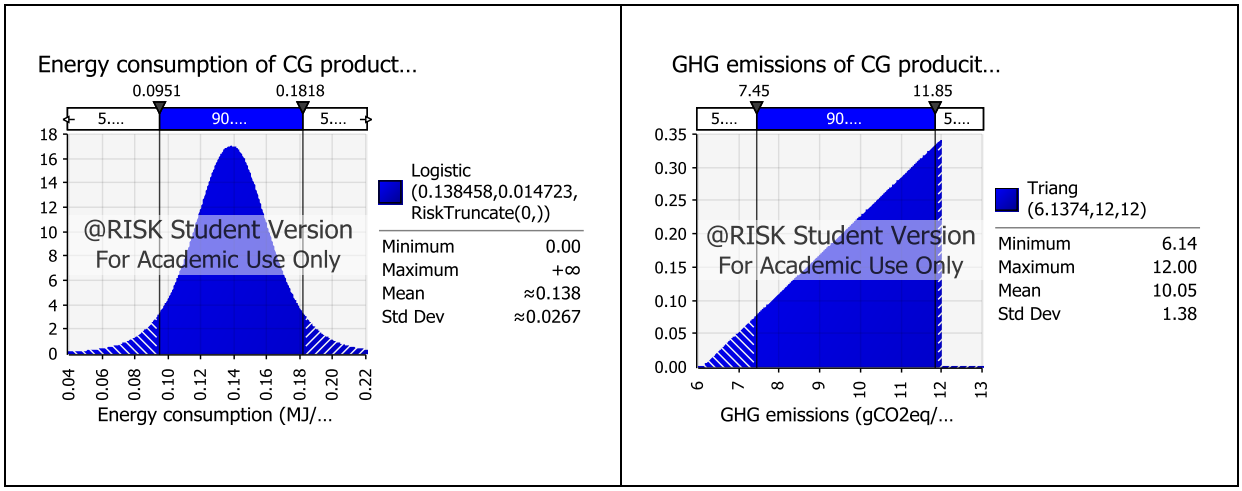


Figure 4.12: The energy consumption and GHG emissions assumptions of conventional gasoline (CG) production in refinery

The distributions in Figure 4.12 above represent an account of the many interactions mainly different models, methodological choices and time frames. The effect of the standard deviation of the energy consumption (±0.03 MJ) and GHG emissions (±1.38 g) on reliability is not very significant with an RSD of ±19% and ±14%, respectively. However, the variance is still considerable and can be attributed in the first place to differences in the allocation methods across the reference models. One of the questions that face researches who conduct life-cycle analysis is how to allocate energy use and emissions for a refinery among its products.

Oil refineries produce a number of different products simultaneously from a single feedstock. Whereas the total amount of energy used by refineries is well documented, there is no simple, non-controversial way to allocate energy and emissions to a specific product (e.g. gasoline). Distributing the resources used in refining amongst the various products invariably involves the use of arbitrary allocation keys that can have a major influence on the results. More to the point, such a simplistic allocation method ignores the complex interactions, constraints and synergies within a refinery and is likely to lead to misleading conclusions. From an energy and GHG emissions point of view, this is also likely to give an incomplete picture as it ignores overall

changes in energy/carbon content of feeds and products. The following methodological review reflects the controversy in allocating energy use and GHG emissions to a specific refinery product.

The GREET model allocates the amount of feedstock and fuels needed to produce a slate of refining products among different products according to the mass of each product and the refining processes necessary for its production (Wang, 1999). Although allocation on a mass basis relates products and co-products using a physical property that is available and easy to interpret, it may not be a good measure for energy functions. Alternatively, the JEC model allocates the energy use and GHG emissions associated with the production of gasoline by modelling how European refineries will adapt to a marginal reduction in demand. The energy consumed and GHG emissions per 1 MJ of gasoline output can be calculated from the change in energy consumption and GHG emissions charged to a gasoline decrement.

In the second place refining crude oil into finished products requires energy (electricity, fuel and steam) and the amount of energy used varies among refineries based on their complexity and the sulphur content of crude oil input. Nonetheless, the variability of the refinery energy consumption and GHG emissions with time is not significant. For instance, in reference to GEMIS v.4.5 database the change in the energy consumption and GHG emissions associated with crude oil refining between 2010 and 2030 is a decrease of only 0.0052 MJ and 1.3 gCO_2eq, respectively, per one Mega Joule of gasoline in vehicle tank.

4.2.3.2 Natural gas conversion

Natural gas from different transportation pathways is transformed to hydrogen in a central reforming plant or else onsite at the refuelling station. Alternatively natural gas is supplied to refuelling stations typically via a low pressure distribution grid (domestic grid) and compressed into CNG for natural gas dedicated internal combustion engines; the compression however is considered in the present study as associated with the natural gas distribution stage, given that the transformation of natural gas to CNG does not involve any feedstock conversion process and thus the fuel production stage is not applicable. Another NG-based pathway considered in the present study includes the conversion of natural gas in a combined cycle gas turbine (CCGT) or a simple cycle gas turbine power plant to electricity.

4.2.3.2.1 Natural gas to gaseous hydrogen in centralized SMR plant

The SMR technology used in commercial hydrogen plants involves conventional, one step steam reforming carried out in high-alloy tubes placed inside a large NG-fired furnace. Natural gas is normally preheated by the waste heat from the reformer's heat recovery section, and the feed gas is processed through a bed of ZnO sorbent to remove the sulfur which poisons the reforming catalysts. Steam is added to the desulfurized NG feed, and the mixture of NG and steam is further pre-heated before entering the reformer, where CH_4 is converted to H_2, CO, and CO_2 by means of nickel-based reforming catalysts. The produced hot synthesis gas at a temperature of 900 – 930 ºC exits the reformer and is cooled by water before entering the shift converter, where shift catalysts convert CO and steam into CO_2 and additional hydrogen gas. The gas from the shift converter is further cooled to ambient temperature before entering a pressure swing adsorption (PSA) unit, where high-purity hydrogen is produced. The PSA off-gas mixture (CO_2, H_2, CH_4, CO, N_2 and some water vapour) is used as a primary fuel for the reformer but a small amount of natural gas is used to supply the balance of the reformer duty. The electricity for the operation of pumps and compressors is purchased from the grid unless the plant is designed to generate and export electricity. Further to improve the efficiency of hydrogen production, combustion air for the burners can be preheated by means of waste heat from the reformer's heat recovery section (Wang, 1999; Spath and Mann, 2001).

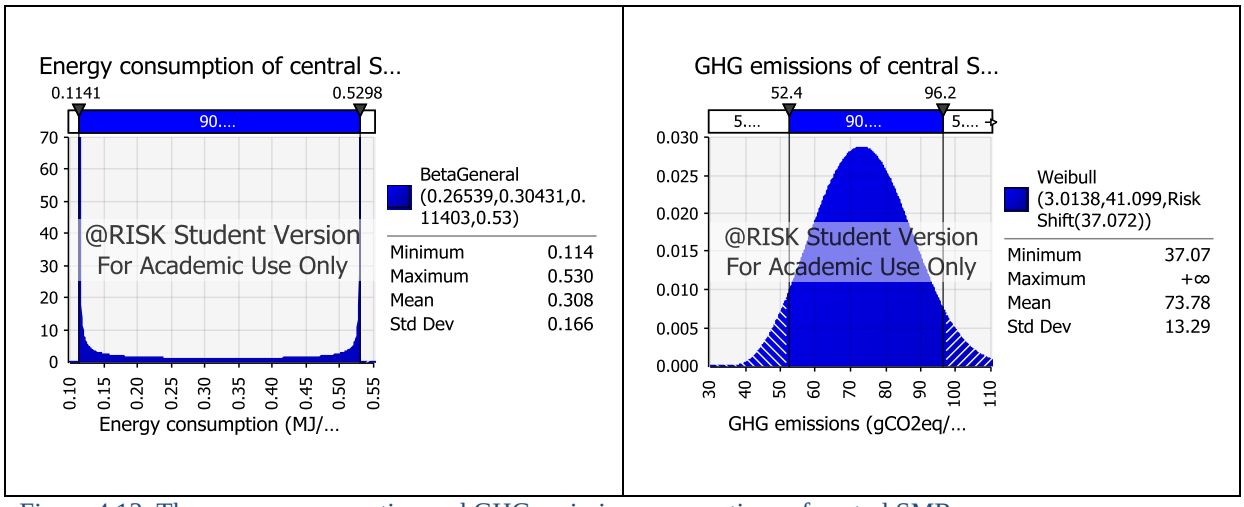


Figure 4.13: The energy consumption and GHG emissions assumptions of central SMR

From the data map in Appendix M the distributions in Figure 4.13 represent inter alia the effect of mainly different models (databases and modelling structures), system boundaries (including the account of process construction) and process design. The size of the standard deviation of the

energy consumption (±0.17 MJ) and GHG emissions (±13.3g) is varying with RSD of ±54% and ±18%, respectively. This reflects that the energy consumption is more sensitive to the variability of the modelling elements as compared to GHG emissions. The variability is attributed in the first place to different databases which may assume different energy conversion efficiencies under default system design (w/o co-products). Most notable is the energy conversion efficiency assumption in the GEMIS v.4.5 database (90.0% under default system design) which is significantly higher than that assumed in other databases including the GREET v.1.8c database which assumes an energy conversion efficiency of 71.5% under default system design. Such variability can be attributed to different reforming yields, operating conditions (e.g. temperature) and proportion of energy recovered.

In the second place, the SMR process design is a major source of variability. The SMR process produces more steam than is consumed by the hydrogen plant. The excess steam can be used by another source and is said to be exported. Alternatively, the excess steam can be used to generate electricity onsite and excess electricity can be exported. The allocation method used to credit the steam/electricity use by another source is substitution where the system is expanded to include the use of the exported energy by the other source. The credit equals the energy consumption and GHG emission associated with the steam/electricity that would otherwise be conventionally generated and supplied to the other source. This opens another source of variability which is the assumption of the type of substituted energy. For instance, the assumption that the electricity substituted is coal-based would result in more credit as compared to assuming that the electricity substituted is NG-based. To reflect the effect of variable SMR process design the author depicts the GREET v.1.8c database assumptions of energy consumption under different process design which spread over a range of 0.28 to 0.43 MJ per 1 MJ of CGH2 in vehicle tank.

4.2.3.2.2 Natural gas to gaseous hydrogen at refuelling stations

Research reveals that the cost of developing the pipeline distribution infrastructure for gaseous hydrogen could be enormous (Wang, 1998). This proven fact dictates the investigation of the option of producing hydrogen at refuelling stations. This approach involves transporting NG through existing pipelines to refuelling stations where small-scale SMR units would be installed to produce gaseous hydrogen. Thus, the pathway includes NG transmission and requires SMR reformers, storage tanks, and compression facilities at refuelling stations.

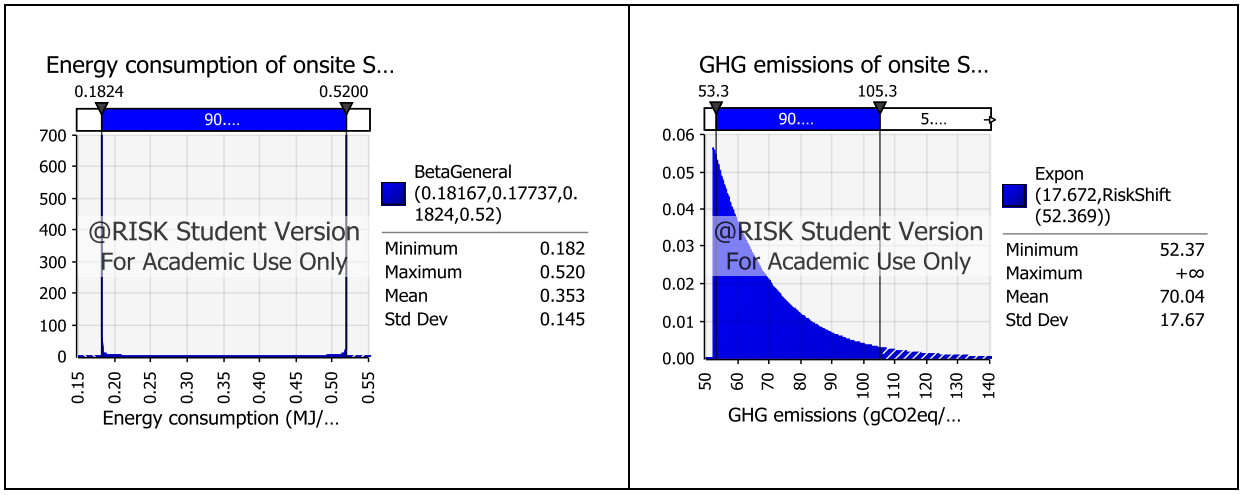


Figure 4.14: The energy consumption and GHG emissions assumptions of onsite SMR

From the data map in Appendix M the distributions in Figure 4.14 represent inter alia the effect of mainly two factors: the different models (databases and modelling structures) and system boundaries (including the account of system construction). The determined standard deviations of the energy consumption (±0.145 MJ) and GHG emissions (±17.7g) give an RSD of ±41% and ±25%, respectively. Thus in line with what was observed earlier with central reforming, the energy consumption is more sensitive to the variability of the modelling elements as compared to GHG emissions. However, in the case of a small-scale SMR unit serving a few or even a single refuelling station the estimated efficiency is lower due to the fact that use of waste heat (energy recovery) would not be practical at that scale.

Therefore the dominant source of variability presented in Figure 4.14 above is the disagreement among the reference databases with respect to the conversion efficiency of onsite reforming. For instance, the conversion efficiency of an onsite reformer is assumed to be 85.0% by the GEMIS v.4.5 model whereas the GREET v.1.8c model assumes a significantly smaller conversion efficiency of 70.0%.

4.2.3.2.3 Natural gas to electricity

Natural gas is extensively used for power generation and this continues to grow as gas replaces nuclear and coal generation as well as cover the bulk of the increasing demand. The electricity generation system types that underpin the system assumptions in Figure 4.15 include mainly CCGT (combined cycle gas turbines), which has a much higher efficiency compared to the conventional thermal steam cycle in utility boilers, and a combined technology of utility boilers (20%), simple cycle gas turbines (36%) and CCGT (44%).

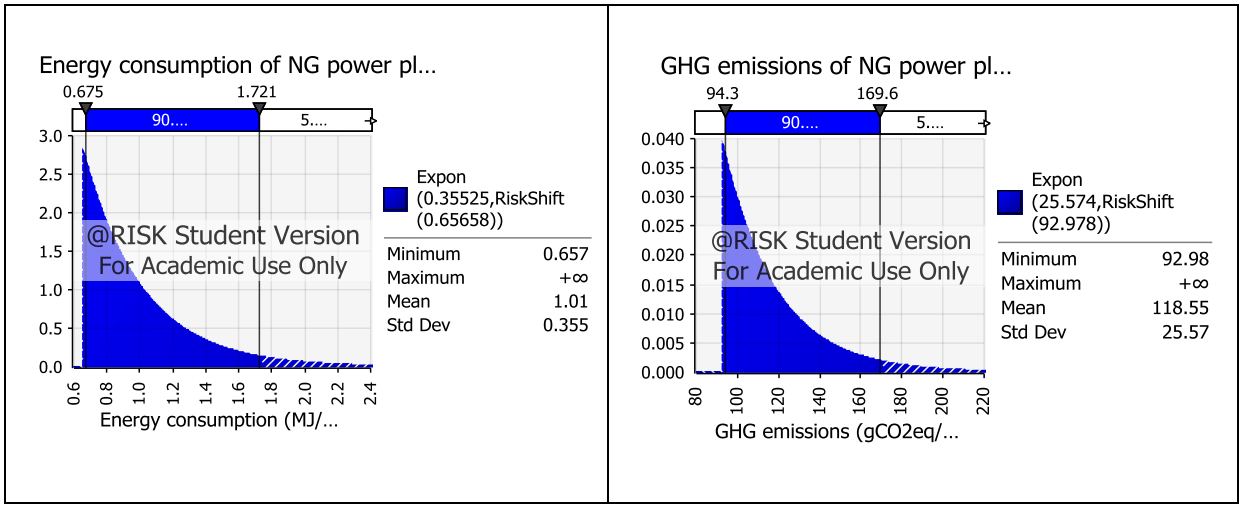


Figure 4.15: The energy consumption and GHG emissions assumptions of NG power plant

The distributions in Figure 4.15 represent inter alia the effect of different models (databases and modelling structure), system boundaries, system types and time frames. The standard deviation of the energy consumption and GHG emissions is ±0.35 MJ and ±25.57 g, respectively. The first and main source of variability is the differences between the reference databases with regards to the conversion efficiency of the power plant under CCGT technology. Also, the large deviation of the combined technology power plant from the average energy consumption (1.012 MJ) results in more variability. Nevertheless, the RSD of the energy consumption and GHG emissions is ±35% and ±22%, respectively. Thus the energy consumption assumption is somewhat more sensitive to the variability of the conversion efficiency as compared to the GHG emissions assumption. The effect of time is not seen as significant where according to the GEMIS model the increase in the efficiency of the CCGT power plant between 2010 and 2030 is only 2%.

4.2.3.3 Conversion of non-biomass renewables

Renewable resources can be directly transformed to electricity and used in electric powertrains. Alternatively, renewable resources can be transformed to hydrogen via centralised electrolysis or at refuelling stations via small-scale electrolysis schemes.

4.2.3.3.1 Hydrogen from central water electrolysis

The electrolysis of water to hydrogen and oxygen is a well established process. It is possible to build electrolysis plants from very small to very large scale. The main source of energy losses in an electrolysis scheme is the electricity needed to overcome polarisation and load-dependant

Ohmic resistance. Moreover, as electrolysis is normally performed under pressure, part of the electricity feed is used for isothermal pressurization (Bossel *et al.*, 2003).

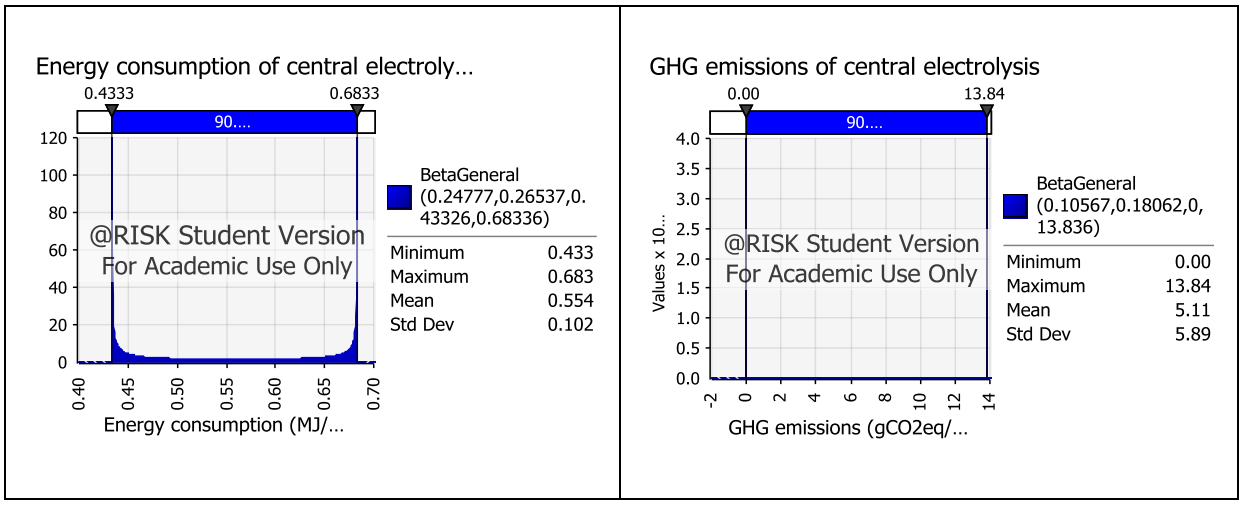


Figure 4.16: The energy consumption and GHG emissions assumptions of central electrolysis

The distributions is Figure 4.16 above represent inter alia the effect of three factors: different models (databases and modelling structure), different system boundaries (inclusion of system manufacturing) and time frames. The standard deviation of the energy consumption is ±0.10 MJ with an RSD of ±18.0. The main source of variability is the different values for conversion efficiency of the electrolyser between different databases. The efficiency of the central electrolyser ranges from 65.0% to 71.5% (for more details on the assumptions of each reference model refer to Appendix M). This includes the increase in conversion efficiency from 67.75% to 70.4% as an effect of development with time between 2020 and 2030 as reported in GEMIS.

The standard deviation of the GHG emissions (±5.9 g) is notably significant given an RSD of ±115%. Where all the other reference models under consideration assume a zero GHG emissions associated with the central electrolysis of water (marginal emissions), the GEMIS model reports GHG emissions as high as 13.8 g of carbon dioxide equivalent. The variability of the GHG emissions is attributed to the difference in the system boundaries between different models where all the reference models except for GEMIS do not account for the GHG emissions associated with the construction of the electrolyser.

4.2.3.3.2 Hydrogen from onsite water electrolysis

As seen in Figure 4.17 the outcome the onsite electrolysis are nearly identical to the outcome for the central electrolysis in Figure 4.16. The small difference in the distribution of the energy

consumption is attributed to the hydrogen LCA model by Bossel (Bossel *et al.*, 2003) which assume a decrease in the conversion efficiency from 69.9% to 60.6% with the down scaling of the electrolyser, but other models assume no change in the efficiency of the electrolyser with size.

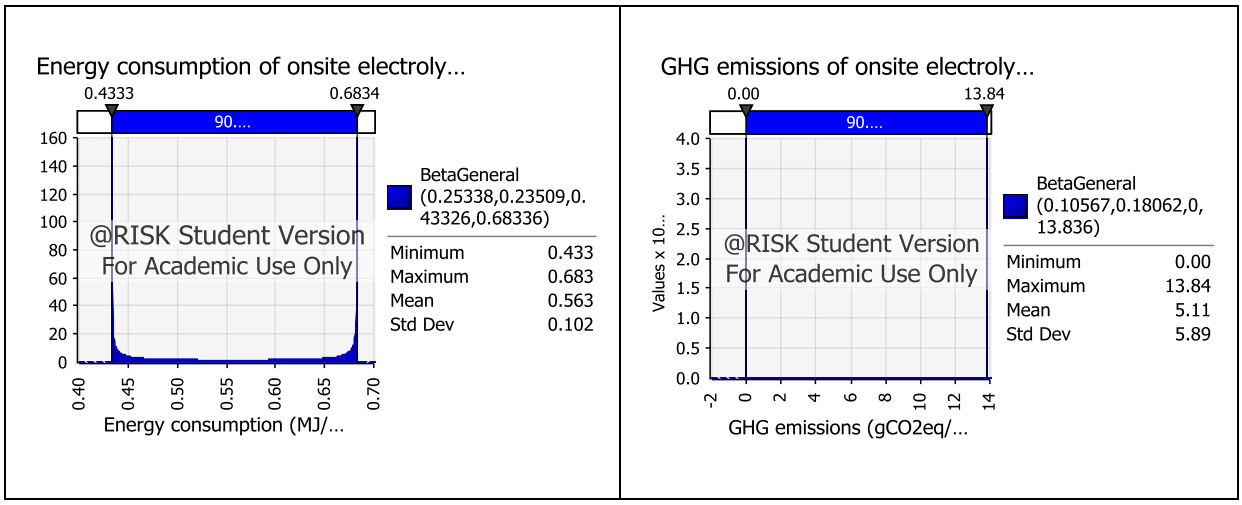


Figure 4.17: The energy consumption and GHG emissions assumptions of onsite electrolysis

According to Bossel *et al*. the smaller the size of the electrolyser, the lower is the current density and the efficiency.

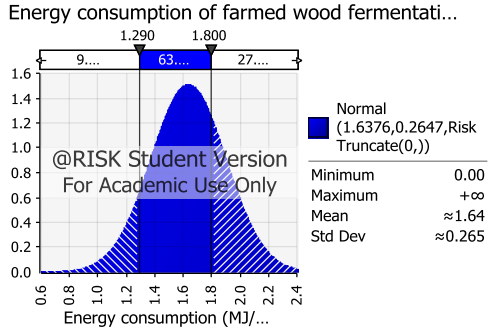
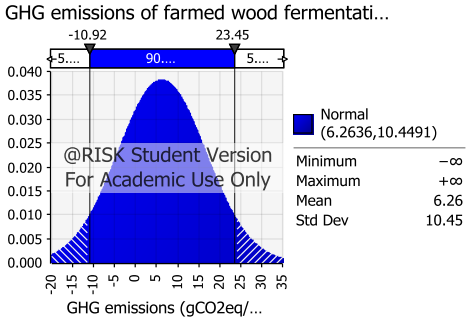
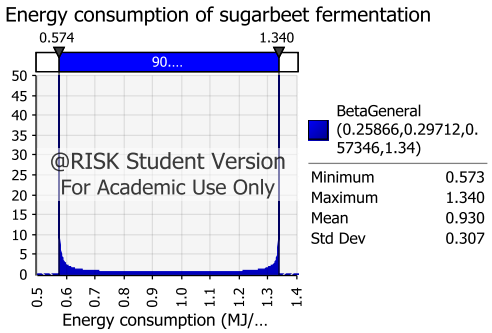
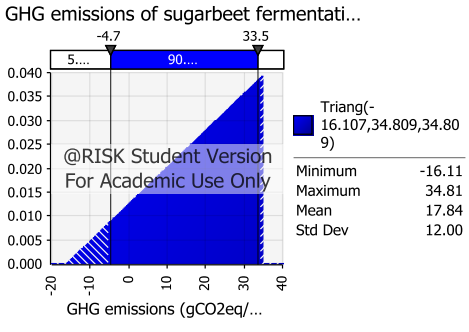
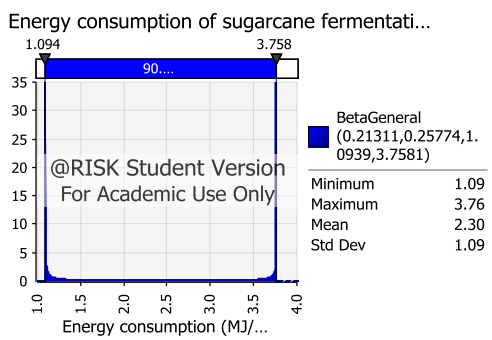
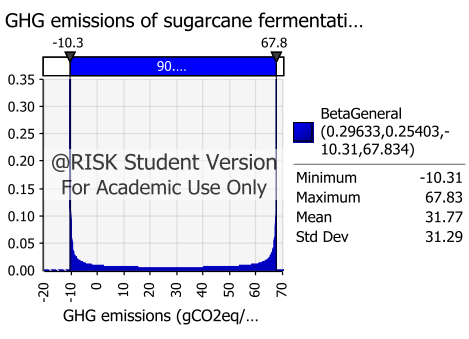
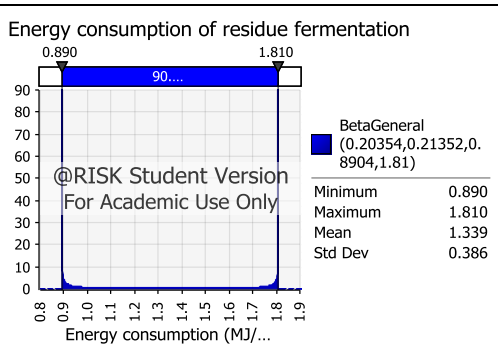
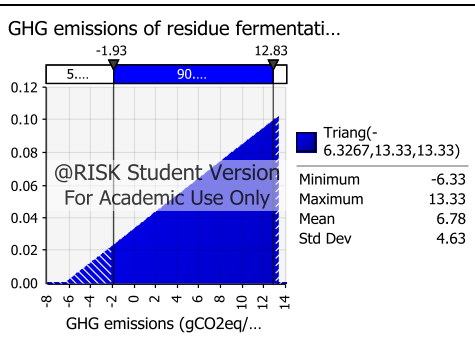
4.2.3.4 Biomass transformation

The transformation of biomass to ethanol through fermentation is a well established and widely used process; however the fermentation of biomass is very energy intensive. Alternatively biomass can be transformed to gaseous hydrogen through a central gasification plant or potentially at the refuelling station through a small scale gasification scheme.

4.2.3.4.1 Fermentation

The following table depicts the distributions of the energy consumption and GHG emissions associated with the fermentation of the different types of biomass feedstock under consideration in the present study.

Table 4.6: The energy consumption and GHG emissions associated with the fermentation of different types of biomass feedstock

	Energy Consumption (MJ/MJ_{EtOH})	GHG Emissions (gCO_2eq/MJ_{EtOH})
Ethanol from farmed wood		
Ethanol from sugarbeet		
Ethanol from sugarcane		
Ethanol from residual biomass		

All types of biomass feedstock under consideration in the present study have cellulosic components (e.g. sugarcane contains high lignin content in the bagasse) or else are completely

cellulosic as in the case of short rotation forestry and residual/waste biomass. The cellulosic type of biomass is fermented in cellulosic ethanol plants where the unfermentable biomass components, primarily lignin, can be used to generate steam (needed in ethanol plants) and electricity in co-generation systems. While combustion of unfermentable biomass components, undoubtedly produces carbon emissions, these emissions are taken up from the atmosphere by the photosynthesis process during the biomass growth, as such carbon emissions from lignin combustion at ethanol plants is treated as zero.

4.2.3.4.1.1 Cellulosic biomass

In referring to Table 4.6 above the standard deviation of the energy consumption and GHG emissions of the fermentation of farmed wood is ±0.26 MJ and ±10.45g, respectively. The variability presented is inter alia the effect of different models (including different databases), methodological choices and system design. All the reference assumptions are based on energy self sufficient systems where the process heat and electricity are supplied from the unfermentable components of wood chips. The variability is mainly attributed to different system designs and allocation methods. The system design determines the amount and type of energy co-generation and the allocation methods determines how the credit from the co-product export is accounted. For instance, the GREET model assume no co-production associated with the production of ethanol from farmed wood, whereas the JEC model assume co-generation of electricity (0.099 MJ per MJ of ethanol produced) and the credit is allocated based on the substitution of electricity from a wood chips fuelled steam turbine power plant. The credit from co-products export explains the negative (< 0) spread of GHG emissions. As different databases may assume different ethanol yields per dry ton of farmed wood, this further affects the variability of the input associated with the fermentation of farmed wood.

Nevertheless, in the case of ethanol from farmed wood all the reference models consider no upstream GHG emissions either as a result of a modelling assumption as in GREET or due to the modelling structures in JEC and GM-LBST which account for the upstream of the feed loss GHG emissions under the account of farmed wood supply.

The fermentation of residual biomass is similarly subject to variability under different databases, system designs and methodological choices. In addition the type of residual biomass (waste

wood, straw, etc) is another source of variability. In reference to Table 4.6 above the standard deviation of the energy consumption and GHG emissions is ±0.39 MJ and 4.6 g, respectively.

The first source of variability is the different types of residual biomass which reflect different ethanol yields per dry ton of residue which is in addition to the differences between different databases in the ethanol yield per dry ton for the same type of residual biomass. The second source of variability is the different system designs and allocation methods. The system design determines the source of the process heat and electricity as well as the amount and type of energy co-generation; and the allocation method determines how the credit from the co-product export is made. For instance, GREET assumes process heat and electricity from corn stover and no co-products; GEMIS assumes heat from ligno straw and auxiliary electricity, and no co-products; whereas JEC assumes process heat and electricity from the non fermentable components of wheat straw and electricity co-generation (0.052 MJ per MJ of ethanol produced) where the credit is allocated based on the substitution of electricity from straw fuelled steam turbine power plant.

Nevertheless, as regards to the variability of the upstream feed loss GHG emissions all the reference models (sample size = 5) except for GEMIS (one sample) do not account for the upstream feed loss GHG emissions. Moreover, GEMIS accounts for the GHG emissions associated with the process manufacturing. Together the process manufacturing and upstream feed loss GHG emissions form a minor source of variability. A change in both the GHG emissions of upstream feed loss and process manufacturing has a significant effect on the total GHG emissions only because on average basis the fermentation process has a very favourable carbon balance and therefore the overall profile is sensitive to external carbon emissions.

4.2.3.4.1.2 Sugar biomass

The sugar resources have cellulosic components such the bagasse of sugarcane which has high lignin content and the pulp of sugarbeet. The cellulosic components are commonly used to supply process heat and electricity.

The fermentation of sugarcane is an energy self sufficient system where the process heat and electricity are supplied from the combustion of bagasse. As such no auxiliary energy is required for the fermentation of sugarcane. The distributions of the energy consumption and GHG

emissions associated with the sugarcane fermentation represent inter alia the effect of an account of mainly different databases, methodological choices, system designs, system boundaries (inclusion of system manufacturing) and timeframes. In reference to Table 4.6 above the standard deviation of the energy consumption and GHG emissions is ±1.09 MJ and ±31.3 g, respectively. As noticed the standard deviation of the GHG emissions is relatively large and significant.

The variability that underpins the standard deviation is multi-sourced and one of the significant sources is the ethanol yield per metric tonne of sugarcane along with the assumed water content. The ethanol yield has a direct effect on the conversion efficiency (efficiency deduced from the energy use and not the energy requirement) and observably ranges from 86.0 l/ t sugarcane (water content not reported) to 98.1 l/ t sugarcane @ 72.5% H_2O. The other significant source of variability is the system design and the allocation method. As mentioned earlier, the system design reflects the type and amount of co-products and the allocation method determines how the credit from the co-products export is accounted. For instance, the GEMIS model assume electricity export (0.05 MJ per MJ of ethanol produced) and the credit is allocated by energy equivalent (no extension of the boundaries to allocate by substitution); the JEC model assume heat export and the credit is allocated by replacement of heat from a light heating oil fuelled boiler; whereas the GREET model assume no co-products. According to the GEMIS database the notable change with time between 2005 and 2030 is an increase in the amount of electricity exported from 0.05 to 0.15 MJ per MJ of ethanol produced, and thus an improvement in the overall efficiency of the system while the conversion efficiency is constant at 20.7%.

Nevertheless, the relatively large variance of the GHG emissions assumption can be tightly attributed to the upstream GHG emissions of feed loss which can have a significant effect on the total GHG footprint of the fermentation process whilst the absolute magnitude of GHG emissions without external emissions (e.g. upstream of feed loss, process construction, etc) is very small. The variability of the upstream GHG emissions of feed loss is large ranging from no consideration, as GREET does not account for the upstream emissions of the sugarcane components used as a process fuel (bagasse) and JEC accounts for the upstream of feed loss under the account of the sugarcane supply, to different assumptions between the LEM and GEMIS databases for the largely variable GHG emissions associated with land use change. For instance, sugarcane produced without the account of land use change would generate much lower

GHG emissions during the supply as compared to sugarcane produced on arable land with the consideration of the GHG emissions associated with indirect land use change. This source of variability does not apply to energy consumption.

In the case of sugarbeet the average energy consumption is significantly lower (0.93 MJ) relative to the average energy consumption associated with sugarcane fermentation (2.30 MJ). The variability is multi-sourced and seems to be primarily an effect of different system designs and allocation methods. The pulp of the sugarbeet can be co-produced as animal feed or alternatively used to generate process heat. For instance, the GEMIS model assumes no co-products and the process heat and electricity are auxiliary: electricity from grid and heat from gas-boiler; the JEC model assume different system designs including: (a) the co-production of pulp credited for replacing animal feed in conjunction with auxiliary process electricity and heat, (b) the co-production of pulp credited for replacing animal feed in conjunction with the partial supply of process heat (0.104 MJ per MJ of ethanol) from the biogas of the sugarbeet slop—the remaining process heat and process electricity are auxiliary, and (c) the co-production of steam from slop and pulp combustion where the credit is allocated by substitution in conjunction with auxiliary process electricity. The GM-LBST model assumes pulp co-production credited by replacing animal feed in conjunction with auxiliary process heat and electricity, whereas the GHGenius model assumes no co-products.

Also present is the variability of the GHG emissions associated with the upstream feed loss. However, such variability is not as very significant as in the case of sugarcane fermentation because most of the assumptions in the sample stem from models which do not account for the upstream GHG emissions under the GHG profile of the fermentation process.

4.2.3.4.2 Gasification

Biomass can be alternatively transformed through central or onsite gasification to gaseous hydrogen and used in FCVs. The following figure depicts the distributions of the energy consumption and GHG emissions associated with the gasification of wood chips.

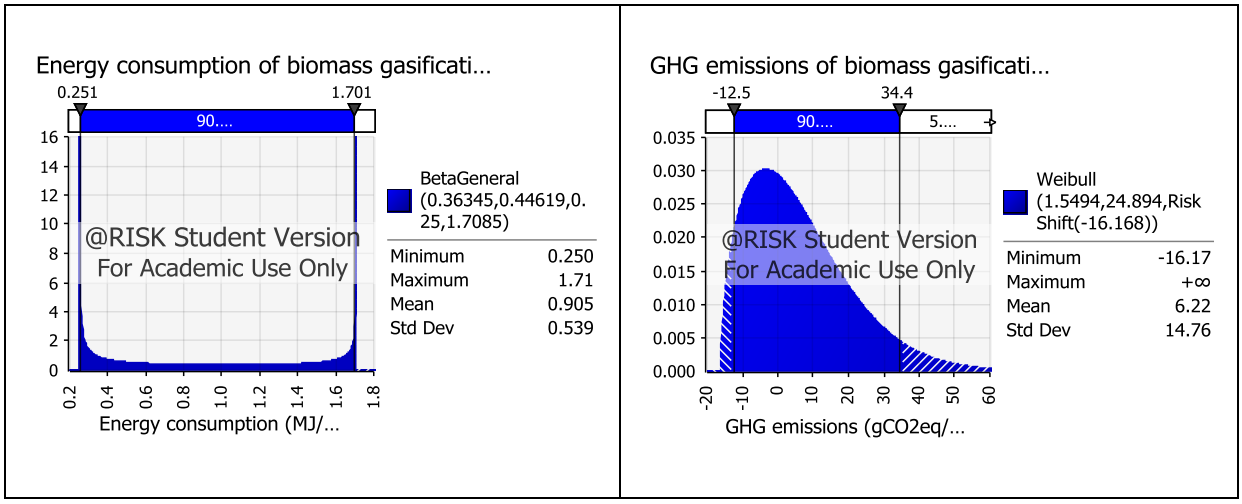


Figure 4.18: The energy consumption and GHG emissions assumptions associated with the production of gaseous hydrogen from wood chips

It is apparent that biomass gasification is a relatively efficient biomass transformation process. However, whether the energy benefits over the fermentation suppress the drawbacks of the need to develop and build an infrastructure for hydrogen storage, distribution, and use remains a matter of further investigation in the present study. In reference to Figure 4.18 the standard deviation of the energy consumption and GHG emissions is ±0.54 MJ and ±14.76g, respectively.

The variability presented is generally an effect of an account of different models (databases and modelling structure), system boundaries (inclusion of system construction), system size, system design and time frames. The presented variability is first attributed to the observed difference in the energy conversion efficiencies under different process fuel mixes and system sizes, e.g. energy recovery is practical in large systems. The energy conversion efficiency apparently ranges from 42.5% to 70.0%, when the system size ranges from 2.5 MW to 200 MW and the process fuel mix is variable including: (i) 100% of the process heat and electricity supplied from wood; (ii) auxiliary electricity for gasification and co-shift reaction, and electricity for PSA from run-off gas engine; and (iii) 95.5% of process fuels from wood, 2.3% of natural gas and 2.2% of auxiliary electricity.

Further, the system design was observed to be a significant source of variability where the observed assumptions include no co-production, steam co-production or electricity co-production. In most cases the co-generation of energy is not considered in small systems (2.5 MW to 10 MW); a notable exception is the GM-LBST model which assumed electricity and/or heat co-generation and export in systems as small as 2.5 MW. There is no observable

disagreement as to the method of allocation and all the reference models that assume systems with co-production use the substitution method in accounting for the credit. However, disagreement can be found regarding the assumption of the replaced system (for example, electricity replaced is either coal-based or NG-based?).

Moreover, the assumption of the gasification of wood through black liquor by JEC formed a clear outlier in the range of energy consumption and significantly affected the variability of the energy consumption. When wood is converted to pulp by what is known as the kraft method, the fibre is released by dissolving the other organic constituents of the wood or non-wood ligno-cellulosics into an aqueous solution containing sodium hydroxide and sodium sulphide. After removal of the fibre (used in paper and pulp industry), the remaining spent solution is called black liquor (Demirbas, 2002). The system presented by JEC is an indirect gasification of wood through black liquor. Their data suggests that the gasification of black liquor is much more efficient than the direct gasification of wood.

A value of zero GHG emissions is associated with the supply of feed loss either as a modelling choice as in the case of GREET or as a result of modelling structure as in the case of JEC and GM-LBST. Nevertheless there is variability in the upstream GHG emissions because GEMIS includes land use change. This causes a variation from 7.2 g to 47.7g of CO_2 equivalent in the sample and had a considerable effect on the variance.

4.2.3.5 Coal conversion to electricity

The consideration of coal in the present study was limited to one pathway for the production of grid electricity. Electricity from coal was investigated in comparison with electricity from natural gas to reflect the limited potential for NG in the transport sector. This originates from the fact that natural gas today is widely displacing coal for power generation and so its use in the transport sector is limited to levels that do not impose the re-use of coal in the power sector. This is due to the fact that any GHG emissions savings gained from the substitution of gasoline with natural gas in the transport sector would be outweighed by coal substituting NG in the power sector.

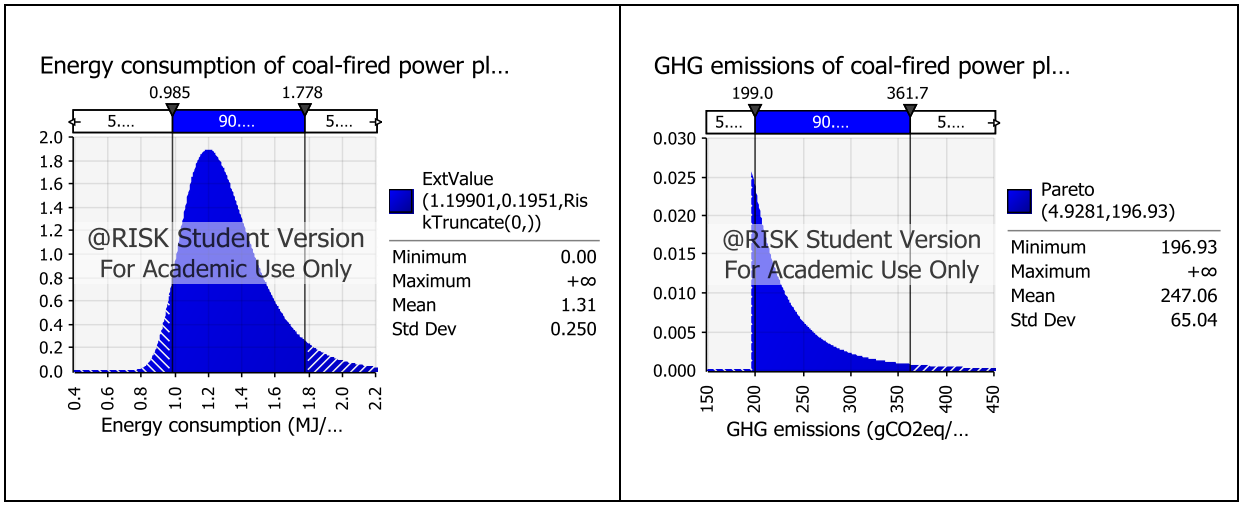


Figure 4.19: The energy consumption and GHG emissions assumptions of coal-fired power plant

The distributions in Figure 4.19 above represent inter alia the effect of different models (databases and modelling structures), system boundaries, system type and timeframes. The standard deviation of the energy consumption and GHG emissions was found to be ±0.25 MJ and ±65.0 g, respectively. Hence the RSD of the energy consumption and GHG emissions is ±19% and ±26%, respectively. In this respect the variability of both the energy consumption and GHG emissions have only a modest effect on the reliability of the assumptions. Nevertheless, the presented variability is primarily attributable to the observed difference in the energy conversion efficiencies across different databases. The energy conversion efficiency of a steam turbine power plant observably ranges from 34.1% to 46.1% and the majority of the systems under consideration are steam turbine based; the only exception is the IGCC (Integrated Gasification Combined Cycle) system from GEMIS which presents a conversion efficiency of 55.0%.

The effect of time was also taken into account where the GEMIS database reported an increase in the efficiency of a steam turbine power plant from 45.4% to 50.1% between 2010 and 2030. The more considerable improvement with time is the decrease of NO_x emissions from 0.106 to 0.062 g per MJ of electricity throughput between 2010 and 2030; however NO_x is not a greenhouse gas and thus the reduction of NO_x emissions lies outside the dimensions measured in the current study.

4.2.3.6 Uranium fuel conversion

The uranium fuel can be used to generate electricity in various types of nuclear reactors. The nuclear electricity from the power plant can be transmitted to the market for use in a Battery Electric Vehicle (BEV) or else converted into hydrogen fuel by electrolysis for use in gaseous hydrogen Fuel Cell Vehicles (CGH2 FCVs).

4.2.3.6.1 Electricity from uranium fuel

In a nuclear reactor the U235 isotope fissions producing thermal energy from which around 35% is converted to electricity. The first source of energy loss is the conversion heat loss which is defined by the thermal efficiency of the power plant. The second source of energy loss is the amount of fuel used for start-up of the auxiliary steam generators and in-plant heating. The published fuel usages range from 0.1 to 3.0 million gallons of gasoline equivalent per year (Delucchi, 1991; Rotty *et al.*, 1975; Bowers *et al.*, 1987); in terms of GHG emissions that is, 0.1 to 6.0 g per kWh of electricity throughput (Fthenakis and Kim, 2007).

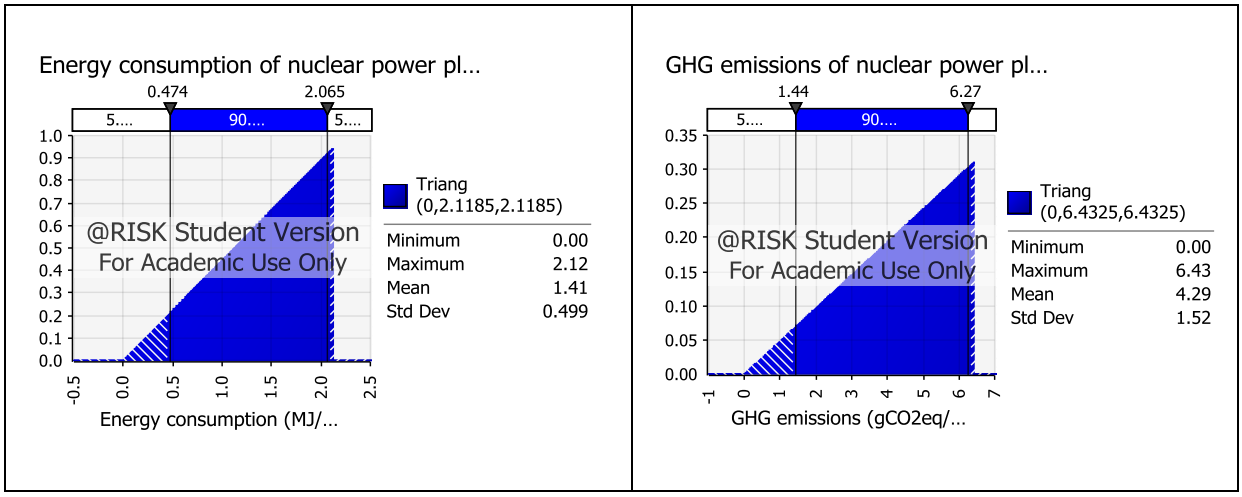


Figure 4.20: The energy consumption and GHG emissions assumptions of nuclear power plant

In all the cases presented earlier in this chapter the distributions describe the statistics of the input sample to the best possible proximity. However, in the case of electricity generation from nuclear fuel the distributions presented in Figure 4.20 are judgemental. The GREET model, unlike GEMIS and JEC, starts the energy account from the electricity generated by the nuclear power plant and thus no account is given to neither the thermal energy loss nor to the fuel usage for start-up and in-plant heating. The GREET model considers the uranium fuel as a material requirement and only accounts for the energy consumption and GHG emissions associated with

the upstream processes of uranium fuel production and transport. The conversion efficiency of a High Temperature Gas-cooled Reactor (HTGR) or alternatively a Light Water Reactor (LWR) is assumed by GREET as 100%. The rationale behind this assumption is presumably the fact that the heat energy value of uranium is zero and thus in LCA it should be accounted as a material requirement like water for electrolysis. In contrast, the GEMIS and JEC models (JEC database adopts data of nuclear systems from GEMIS) account for the uranium fuel in terms of the heat generated by fission per one gram of uranium fuel. Therefore, the GEMIS and JEC models consider the thermal efficiency of the plant and account for the thermal losses; in addition both models account for the start-up fuel usage. The conversion efficiency of a Pressurized Water Reactor assumed by GEMIS and adopted by JEC is 33%. In addition these models account for the energy consumption and GHG emissions associated with the construction of the power plant.

The distributions in Figure 4.20 above show significantly lower standard deviation (±0.50 MJ) as compared to the standard deviation of the input sample (±1.21 MJ). In fact the distributions are assumed with a bias for the methodology employed by GEMIS. The introduced bias is visual where the population is shifted towards the GEMIS assumption by the triangular distribution. Thus the mean was significantly increased and the standard deviation was significantly downsized to better represent reality. The reason behind this interference is the author's belief that the methodology employed by GREET is not valid and should not be given the same weight in the present standardization.

4.2.3.6.2 Hydrogen from nuclear electricity

The uranium fuel can be used to generate hydrogen fuel after conversion into electricity in a nuclear reactor. In reference to the data map in Appendix M the distributions in Figure 4.21 represent to the best proximity inter alia the effect of an account of mainly different models (databases and modelling structures) and system boundaries.

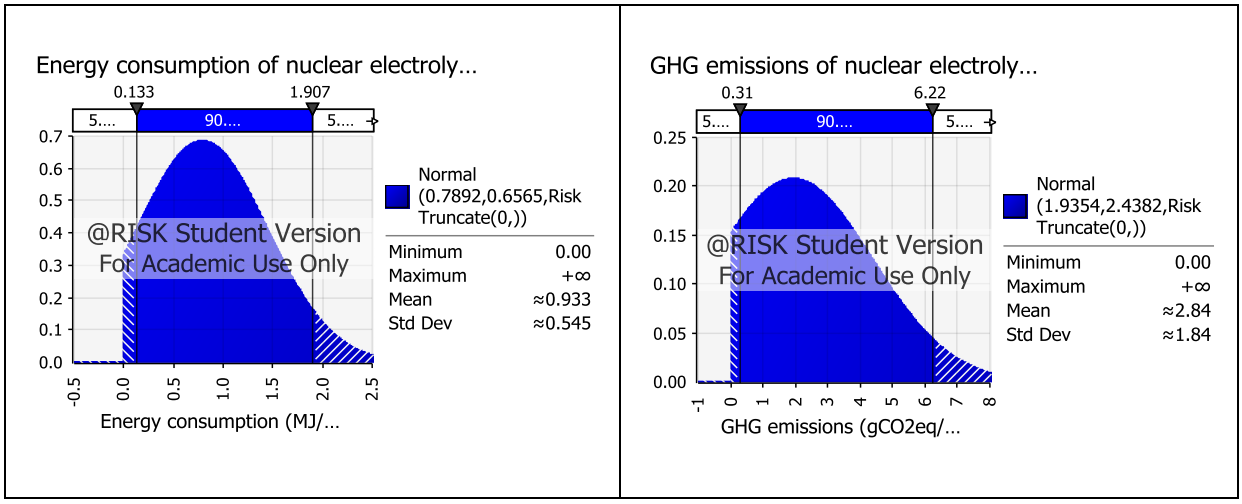


Figure 4.21: The energy consumption and GHG emissions assumptions of electrolysis by nuclear electricity

The standard deviation of the energy consumption as presented is ±0.54 MJ and forms more than 50% of the mean. This is primarily attributed to differences in the upstream account of energy consumption across different models. As seen from the distribution of energy consumption, the electricity loss in the electrolysis process is on average 0.93 MJ per MJ of electricity "in tank". A significant amount of energy use is associated with the supply of the electricity loss and the discrepancy in the assumptions of this account across the reference models is the main source of variance. For instance, the GEMIS model has the largest upstream energy consumption. This accounts for the energy use for UF_6 production (no uranium loss), enrichment by 100% diffusion, thermal loss, start up fuel usage and construction of nuclear power plant. On the other hand the GREET model has the smallest upstream energy consumption. In this case this includes the energy use for UF_6 production (no uranium loss), enrichment by mainly centrifuge (75% centrifuge), 100% nuclear plant efficiency (uranium is accounted as an active material rather than an energy resource) and no allowance for system construction. The JEC model does not account for the upstream energy at all in the fuel production stage (under the semi-real modelling structure in this model the upstream of the process fuels is accounted for in the upstream stages of the chain).

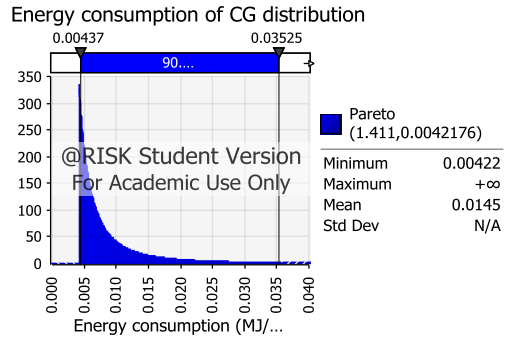
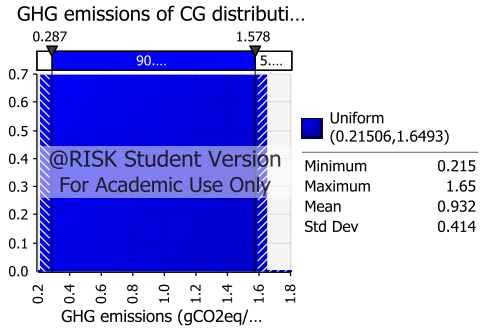
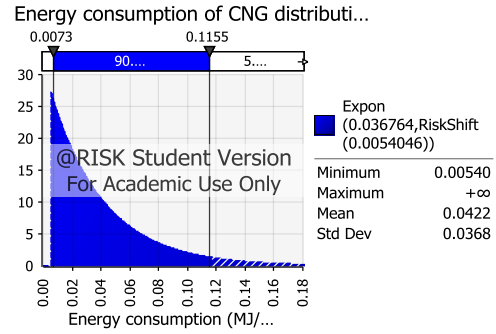
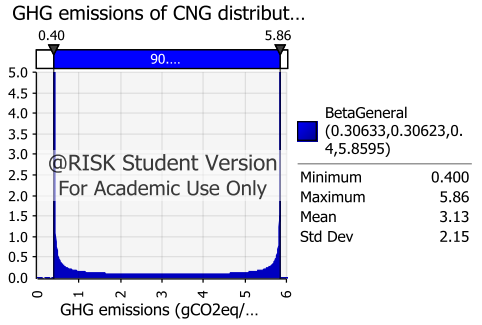
The second source of variability is the differences across the reference databases with regard to the conversion efficiency of the electrolysis. The GREET model assumes the largest conversion efficiency (77.8%) and thus the smallest electricity loss; the GEMIS and JEC models, however, assume a conversion efficiency of 67.5% and 65.0%, respectively.

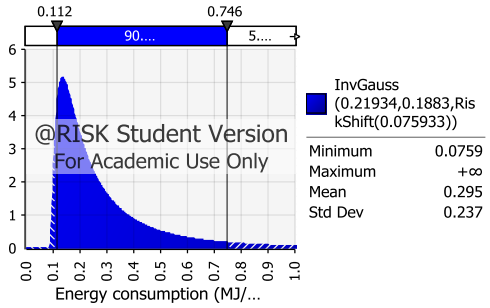
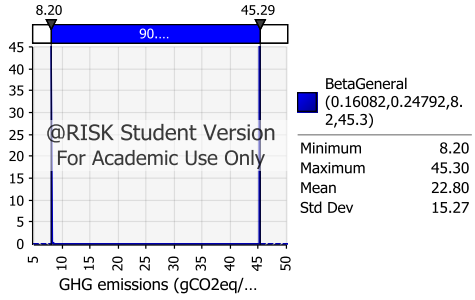
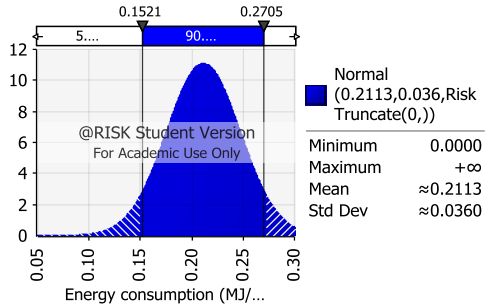
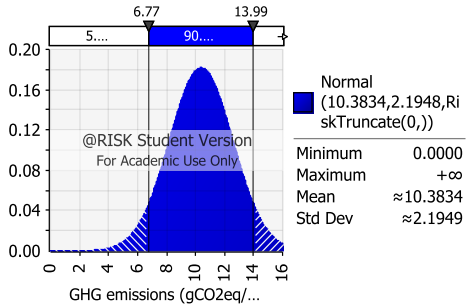
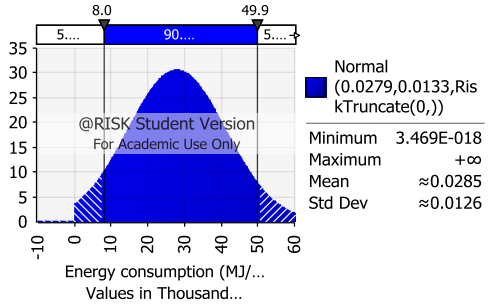
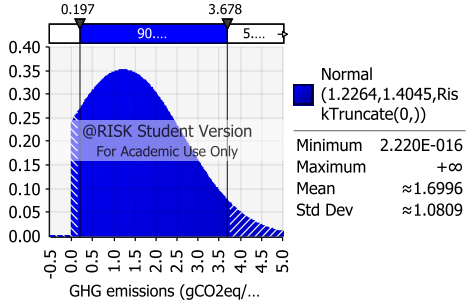
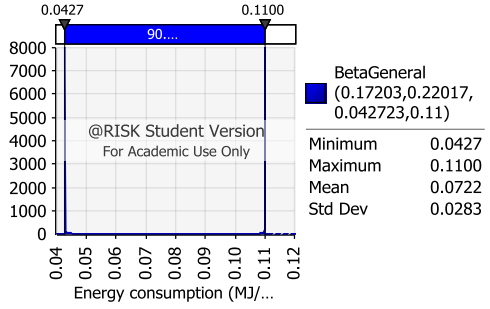
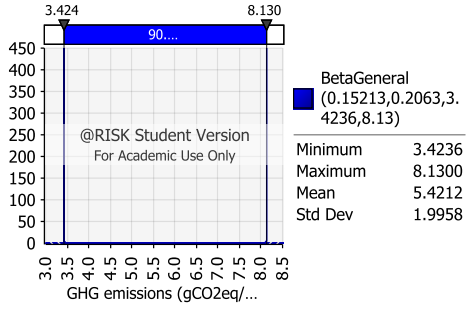
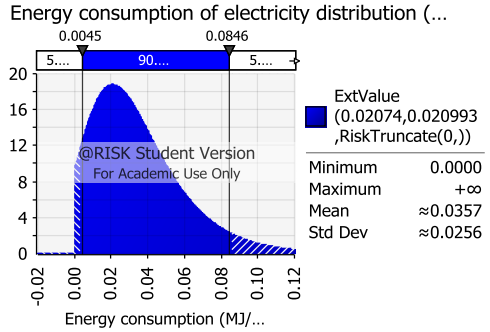
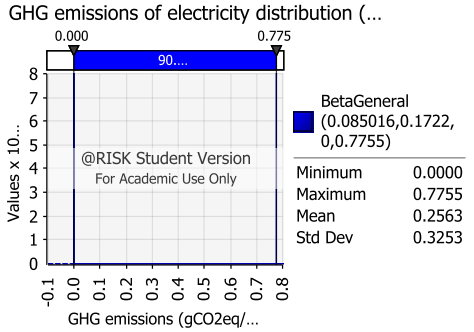
The marginal GHG emissions associated with the electrolysis process is zero and thus the reported emissions are the upstream emissions associated with the supply of the process fuel (electricity loss). As such, the variability of the GHG emissions (±1.84 g) as presented in Figure 4.21 above is primarily attributed to the differences in the modelling structures where the JEC model does not account for the upstream GHG emissions of the process fuel (electricity loss) in the GHG footprint of the electrolysis process. Moreover, the differences in the assumptions of the upstream GHG emissions across the reference models form a minor source of variability.

4.2.4 Fuel distribution

The following table depicts the distributions of the energy consumption and GHG emissions associated with the distribution of the different types of fuel under consideration in the present study.

Table 4.7: The energy consumption and GHG emissions associated with the distribution of different types of fuel

	Energy Consumption (MJ/MJ_{Fuel})	GHG Emissions (gCO_2eq/MJ_{Fuel})
Conventional gasoline (CG) distribution		
CNG distribution		

CGH2 distribution (central)	Energy consumption of CGH2 central distributi... 	GHG emissions of CGH2 central distributi... 
CGH2 distribution (decentral)	Energy consumption of CGH2 decentral distributi... 	GHG emissions of CGH2 decentral distribut... 
LH2 distribution	Energy consumption of LH2 distribut... 	GHG emissions of LH2 distributi... 
Ethanol distribution (sugarcane ethanol)	Energy consumption of SC ethanol distributi... 	GHG emissions of SC ethanol distribut... 
Electricity distribution (LV user)	Energy consumption of electricity distribution (... 	GHG emissions of electricity distribution (... 

In general, in the distribution of liquid fuels such as gasoline and ethanol the primary source of variability is the distance between the fuel production site and the user site. The distribution of gasoline follows a chain from refineries to terminals by ship, pipeline and/or train, transfer to road tankers, haulage to refuelling stations and finally dispensing into the vehicle tank. The distances under consideration in the STM include both short and long distances for example (i) 100 km transfer via truck tanker to nearby stations; and (ii) 500 to 530 km inland navigation (ship) plus pipeline distribution plus 90 to 250 km of distribution via train to depot plus 50 to 150 km transfer from depot via truck tanker to stations. Ethanol is distributed in much the same way as gasoline; however, its distribution uses considerably more energy compared to gasoline, for two reasons. First, it has less specific energy content. Second, it is assumed to travel longer distances from a limited number of production sites. The distribution of sugarcane ethanol in the STM includes the overseas transportation of ethanol from Brazil to a European port and distribution for use as a transportation fuel.

On the other hand, the variability of gaseous fuels such as CGH2 and CNG is predominated by the distribution pressure and type of fuel for compression. (The latter factor only has impact on the GHG emissions.) The natural gas is distributed for use as a transportation fuel in the form of CNG. The distribution of NG as a transportation fuel in the STM does not include its transfer to the refuelling station and mainly consists of the compression of NG to CNG. Hydrogen from electrolysis or SMR central plants is either transported by pipeline to refuelling stations where it is compressed and dispensed, or else liquefied nearby the central plant and transported to refuelling station by road where it is vaporised/compressed and dispensed into the vehicle tank. Alternatively hydrogen produced onsite (in the refuelling station) is directly compressed and dispensed into the vehicle tank. Nevertheless, the hydrogen distribution with LH_2 as an intermediate is very energy intensive requiring 430 MJ of electricity per 1 GJ of liquid hydrogen, and significant evaporative losses occur due to boil off (IEA, 1999). The same energy intensity applies to the compression of hydrogen to LH2 in the central plant for use as a transportation fuel.

4.3 Vehicle operation (TtW)

Although the TtW stage as seen in Table 4.8 in Section 4.4 has a large impact on the overall result, the technical details of the vehicle model are not the main focus of the current project. The coverage given is adequate to probe the variability of the vehicle performance.

Earlier in Chapter 3 encountered the measurement of the correlations between the performances of the different types of vehicles such as CG ICEV and CNG ICEV and others under the combined effect of changes in the modelling elements of the reference models was encountered. In this case for every possible event there is one corresponding event from the other references and therefore the correlations can be accurately measured between the TtW variables of different STMs.

As mentioned earlier it was observed that the correlations between the performances of the different types of vehicles under the changes in the modelling elements across the reference models which include the JEC, GREET, GM-LBST, MIT and LEM is nearly +1 and thus the performances of the different types of vehicles move in perfect tandem. The only explanation to this observation is that the effect of the combined change in the modelling elements between the different reference models is dominated by the effect of changes in factors that simultaneously affect the performances of the different types of vehicles in an equally proportional manner. In fact the only factors that can have such an effect are the driving cycle, vehicle weight and time frame which simultaneously affect the performances of the different types of vehicles. This observation makes it evident that the changes in the other modelling elements such as the database and the vehicle design across the reference models do not have a significant impact on the vehicle performance, and that the changes in the driving cycle, vehicle weight and/or time frame are the predominant sources of difference between the assumptions of the reference models.

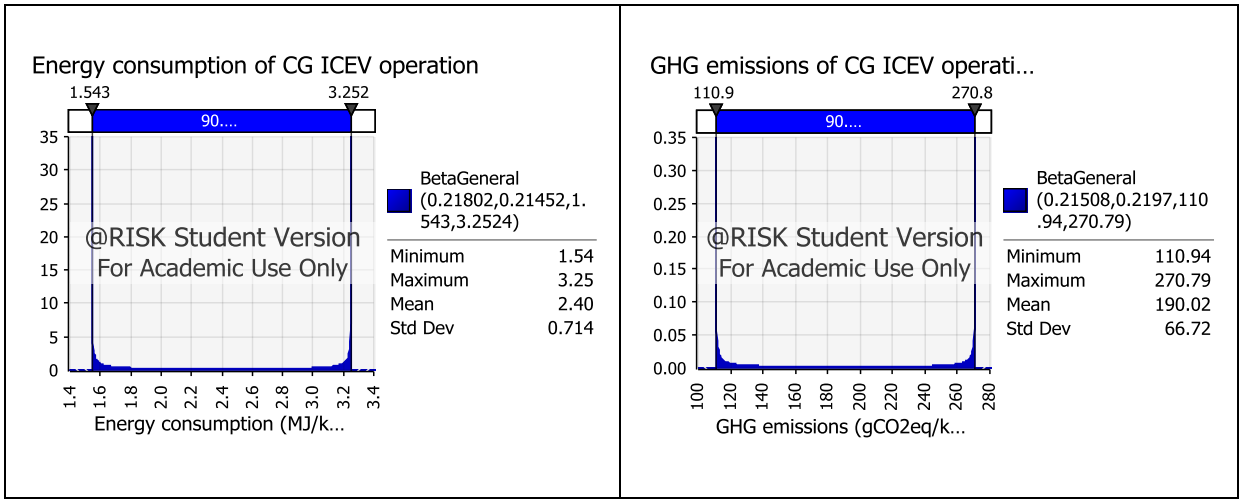


Figure 4.22: The energy consumption and GHG emissions assumptions of the CG ICE vehicle operation

The variability presented in Figure 4.22 is not mainly due to variation in the time frame because all the reference models except for MIT (Weiss *et al.*, 2000) assume a time frame around 2010. Thus the primary sources of variability are the variation in the driving cycle and vehicle weight assumptions across the reference models. (This is the case with all types of vehicles.) The large impact of the vehicle performance on the system performance (refer to Section 4.4 below) makes it evident that the driving cycle and vehicle weight assumptions are critical assumptions in the WtW modelling of alternative transport systems. Herein the STM provides unprecedented reliability by buffering against non-realistic driving cycle assumptions and variation of vehicle weight. Given the variation between the major models it is only sensible when undertaking a global analysis, to pool available data in a statistically sensible manner.

4.4 The summary of the major sources of variability

Based on the results of the sampling based sensitivity analysis which are documented in Appendix T and the analysis of the input uncertainty undertaken in the current chapter the major sources of variability for the main pathways under study are presented in Table 4.8 and discussed below.

Group	The major factors that underpin the variability of the WtW energy consumption	The major factors that underpin the variability of the WtW GHG emissions
CG from Crude Oil	Index A: 90% A1- CG ICEV efficiency	Index A: 85% A1- Emissions from CG ICEV
CGH2 from NG	Index A: 66% A1- CGH2 FCV efficiency Index B: 11% B1- SMR conversion efficiency	Index A: 53% A1- Emissions from CGH2 FCV Index B: 17% B1- Emissions from SMR

	(account of process fuels including feed loss per output) B2- Plant design (co-products) B3- Allocation method and type of displaced system Index C: 11% C1- Distribution pressure	B2- Plant design (co-products) B3- Allocation method and type of displaced system Index C: 14% C1- Distribution pressure (from suction to discharge) C2- Type of compression fuel
CNG from NG	Index A: 86% A1- CNG ICEV efficiency Index B: 7% B1- NG feedstock transport mode B2- NG feedstock transport distance	Index A: 74% A1- Emissions from CNG ICEV Index B: 11% B1- NG feedstock transport mode B2- NG feedstock transport distance Index C: 6% C1- CNG ICEV efficiency
Electricity from NG	Index A: 74% A1- BEV efficiency Index B: 16% B1- Power plant efficiency (across different types of technology)	Index A: 69% A1- Emissions from BEV Index B: 19% B1- Emissions from NG power plant (across different types of technology)
Ethanol from Biomass	Index A: 49% A1- Fermentation yield A2- Plant design (co-products) A3- Allocation method and type of displaced system Index B: 45% B1- Ethanol FCV efficiency	Index A: 55% A1- Fermentation yield A2- Plant design (co-products) A3- Allocation method and type of displaced system A4- Upstream emissions from the supply of feed loss (also relates to the land use change assumption) Index B: 25% B1- Land use change assumption B2- Fertilizers use (N_2O emissions)
CGH2 from Biomass (wood)	Index A: 52% A1- Gasification plant size and design A2- Type of displaced system Index B: 42% B1- CGH2 FCV efficiency	Index A: 35% A1- Land use change assumption + fertilizers use across two types of feedstock (waste and cultivated wood) where in the case of waste wood the emissions from LUC and fertilizers use are not applicable Index B: 31% B1- Gasification plant size and design B2- Type of displaced system B3- The upstream emissions of the supply of feed loss Index C: 12% C1- Distribution pressure and type of compression fuel
Electricity from Renewables	Index A: 83% A1- BEV efficiency Index B: 8% B1- Energy associated with power generation process construction and/or operation	Index A: 90% A1- Emissions associated with power generation process construction and/or operation Index B: 6% B1- BEV efficiency
CGH2 from Renewables	Index A: 77% A1- CGH2 FCV efficiency Index B: 6% B1- Electricity loss in electrolysis Index C: 4% C1- Energy associated with power	Index A: 29% A1- Emissions associated with power generation process construction and/or operation Index B: 22% B1- Distribution pressure and type of

	generation process construction and/or operation	compression fuel Index C: 22% C1- The upstream emissions associated with the supply of electricity loss (also relates to the emissions from the construction and/or operation of the power plant)
Electricity from Uranium	Index A: 66% A1- BEV efficiency Index B: 25% B1- The thermal losses associated with power generation	Index A: 61% A1- BEV efficiency Index B: 23% B1- Emissions associated with the nuclear plant construction
CGH2 from Uranium	Index A: 61% A1- The thermal losses associated with power generation Index B: 26% B1- CGH2 FCV efficiency Index C: 7% C1- The upstream energy consumption associated with the supply of electricity loss in the electrolyser (also relates to the thermal losses of the power plant)	Index A: 67% A1- Distribution pressure and type of compression fuel Index B: 17% B1- CGH2 FCV efficiency
Electricity from Coal	Index A: 88% A1- BEV efficiency Index B: 10% B1- Coal power plant efficiency (across different types of technology)	Index A: 69% A1- BEV efficiency Index B: 20% B1- Emissions from coal power plant (across different types of technology)

Table 4.8: The major factors that underpin the variability of the STM output

As shown in Table 4.8, for each option the considerable sources of variability of the stages that are responsible for the majority of the overall output variability have seen listed. The impact of these stages is reflected by the indices from the sampling based sensitivity analysis which estimates the contribution of each stage of the model to the variability of the output. (The index calculation is depicted in Eq. 3.25 in Chapter 3). However, in listing the considerable sources of variability for each significant stage of the model there is no differentiation between their relative impacts. For further information the reader is referred to the earlier sections in which the richness of the analysis has been detailed.

Based on the analysis presented in Table 4.8 above the author discusses some points that are important for the results analysis and discussion in the following chapter (Chapter 5). In general, the STM stages that have major impact on the output are the vehicle operation (TtW), fuel production and feedstock production. The output of chains of fossil fuel driven vehicles is predominated by the variability of the vehicle performance including energy consumption and GHG emissions, and are insignificantly sensitive to the fuel chain (WtT) stages. Nonetheless, in

general, the WtT stages of the chains of non-fossil driven vehicles have better impact on the energy consumption output and a large impact on the GHG emissions output. (The impact of the WtT stages of the BEV chains on the GHG emissions output is moderate.)

In the following chapter (Chapter 5) the potential of the different systems under study will be discussed. The potential of a system is relative to the reference chain (the crude oil based chain). Overall the optimization will aim to maximize the guaranteed energy and GHG emissions savings as a result of the alternative system displacing the conventional system. In fact this is achieved through the optimization of the WtT stages and not the TtW stage as the assumption of an alternative vehicle of optimum performance will be in favour of the conventional chain over the alternative chain because of the paired behaviour between the performances of the alternative and conventional vehicles. In this respect one measures the capacity of the system optimization relative to the reference chain from the impact that the WtT stages have on the output. Yet not all sources of variability form a strategic choice for the optimization of the system.

In the case of CGH2 and electricity from NG chains there is only a moderate capacity for optimization mainly through the fuel production and includes the hydrogen distribution in the case of CGH2 chains. Nevertheless, in the case of biomass-based chains in excess of 50% of the output variability is related to the stages of the fuel chain; in fact for the GHG emissions output in excess of 80% of the variability is related to the stages of the fuel chain. Thus in the case of biomass-based chains there is a large capacity of optimization for the energy consumption mainly through the energy intensive fuel production and even a much larger capacity for the GHG emissions output which is sensitive to the feedstock cultivation where the emissions from land use change and fertilizers use can be very significant.

In the case of CGH2 and electricity from renewables chains there is a large capacity for optimization of the GHG emissions mainly through the emissions associated with the construction and/or operation of the power generation process. However, the WtT stages have insignificant impact on the energy consumption output which is predominated by the vehicle performance and thus there is no considerable capacity for optimization of the energy consumption.

Interestingly, the assumption of the thermal losses in the nuclear power plant operation has large impact on the energy consumption of the uranium based electricity chain and moderate impact

on the energy consumption of the uranium based CGH2 chain. This has been discussed earlier in this chapter where there is a disagreement between GREET and other models. To re-emphasize according to LBST (2008) the E3 database tool employed by the JEC model uses the so-called efficiency method for the calculation of energy consumption (similar to the procedure adopted by international organizations such as the EUROSTAT and IEA) where the efficiency of electricity generation from nuclear power is based on the heat released by nuclear fission; thus in this method the thermal losses in the power plant are accounted. On the contrary, GREET believes that in the life cycle analysis we account for the energy material in its heat value and in the case of uranium which does not have a heat value (not combustible) it is accounted as an auxiliary material such as the fertilizers in the farming process. Thus according to GREET one should not account for the uranium losses in terms of energy but only account for the energy consumption to produce and supply the uranium as an auxiliary material for the nuclear power plant. Although a bias was introduced for the efficiency method in the definition of the input distributions for nuclear power generation (Section 4.2.3.6), still the thermal losses in the nuclear power generation have a major impact on the energy consumption output.

Finally, the capacity of optimization for the energy consumption in the case of the coal based electricity chain may not be significant, however that for the GHG emissions is much better mainly through the GHG emissions from the coal power plant.

5 Results Analysis and Discussion II: Uncertainty Analysis

5.1 The criteria of comparison

The clear identification of the criteria under which the different options under study are compared is essential. It was mentioned earlier in Chapter 2 that the "criterion of comparison between different options based on the standardized results is *sustainability* in its energy and environmental perspectives" and a sustainable action is "that which meets the needs of the present without compromising the ability of future generations to meet their own needs." In fact each of the alternative options under study in the current thesis displaces the conventional option which is defined by the production, distribution and use of conventional gasoline (CG) for use in an internal combustion engine vehicle (ICEV). The question of interest herein is: What is the impact on sustainability from each action of displacement? In this respect the impacts sought are: (i) the maximal reduction in the depletion of exhaustible energy resources per activity (i.e. km), (ii) the best increase in the efficiency of using non-exhaustible resources (capacity) for overall decrease in dependency on exhaustible resources, and (iii) strong curbing of GHG emissions. The options under comparison in this chapter are grouped based on the type of resource used: natural gas, non-biomass renewables (renewables excluding biomass), cellulosic biomass, sugar biomass, coal and nuclear. Detail consideration of each is to be found in Sections 5.3 to 5.7.

5.1.1 Comparison of chains based on exhaustible resources

In the comparison of chains mainly based on exhaustible resources such as fossil fuels the competing chains are compared based on the change in the energy consumption and GHG emissions from the displacement of the conventional chain. The change in the energy consumption may represent an increase or a decrease in the depletion of exhaustible resources per activity (i.e. km) which has direct impact on sustainability in terms of energy. The depletion of exhaustible energy resources implies that we are taking away useful Mega Joules from future generations and this means less sustainability according to the definition as stated above. (The goal as set by the concept of sustainability is to minimize losses in the use of exhaustible resources and avoid, as far as possible, compromising the ability of future generations to meet their own needs.) On the other hand, the change in the GHG emissions has direct impact on sustainability in its environmental terms.

Nevertheless, in generating the change distribution (e.g. the distribution of change in energy consumption) which is the subtraction of the alternative chain distribution from the conventional chain distribution the two input distributions may not be independent in reality. For instance, as shown in Figure 5.1 although the gasoline ICEV distribution considerably overlaps with the gasoline ICE HEV distribution, this does not mean that the hybrid vehicle can have more energy consumption compared to the associated non-hybrid one as that would be unrealistic. Herein the author highlights one of the most important features of the STM outputs; in a simulation the output of one chain can be probed and correlated with the output of another chain. Simulations to sample from the alternative chain as well as the reference chain were set up and the difference computed taking into account the correlations between the two output distributions. By estimating correlation coefficients between each alternative chain and the reference chain based on the common major elements of variability as explained in Section 3.3.3 in Chapter 3 simulations were made to produce a distribution of the change in energy consumption or GHG emissions (see Figure 5.2 for an example of the distribution of change in energy consumption). Such a distribution is the first-of-its-kind in the field of energy systems analysis and reflects as complete a population as possible of what may occur in reality in terms of direct impact on sustainability. The provision of such distributions was not possible without synthesizing an aggregate of possibilities under variable modelling elements as done using the STM.

5.1.2 Comparison of chains based on non-exhaustible resources

When one thinks about maximizing the efficiency of a chain based on an exhaustible resource one wants to maximize the net positive impact on sustainability in terms of energy by decreasing the global depletion in energy resources per activity (i.e. km). On the other hand, whether the resource is exhaustible or non exhaustible, given a certain amount of resource in hand one wants to use it in the most efficient route possible to benefit from indirect positive impacts on sustainability.

The comparison of the energy consumption for chains based on exhaustible resources with the conventional chain which is also based on an exhaustible resource, namely crude oil, is meaningful as it reflects the direct savings (or depletion) in exhaustible resources as a result of an alternative system replacing the conventional system. The option that brings the largest energy savings relative to the conventional option has the largest positive impact on sustainability in

terms of energy. However with regard to sustainability and for chains based on renewables, the energy change relative to the reference chain is almost meaningless because the consumption of renewable resources in principle does not take away Mega Joules from future generations; renewable resources are non-exhaustible.

In fact the unlimited abundance of renewable resources should not be mistaken for unlimited availability. Renewable resources such as wind and solar energy are limited to the number of renewable power sources that can be developed and are acceptable to the society. In the same way the biomass type of renewables are limited by land availability. Therefore by the use of this precious non-exhaustible resource one can first make large positive impact on sustainability in terms of energy, as well as in terms of CO_2 emissions to a lesser extent, from the direct displacement of fossil fuels. Secondly, by making best use of this precious resource one encourages less use of fossil fuels per demand of energy and benefits from indirect positive impact on sustainability. Thus the options based on renewables are compared directly to each other in terms of energy consumption following the goal of making best use of renewable resources by considering the systems of highest energy efficiency.

5.2 System optimization

The question that should be addressed in the comparative analysis of different alternative options is: What are the strategic choices to be made? Herein the expected ability of the alternative system to generate savings relative to the conventional system is assessed. Consideration is also given to the risk that there will be no savings. The risk is the risk of energy or GHG emissions debt from the displacement of the conventional system. On the other side of the change distribution the possibility of high energy or GHG emissions credit is seen as an opportunity. Thus the general goal is to think about the improvement of the average performance of the alternative chain relative to the conventional chain. In graphical terms this means decreasing the overlapping population between the two distributions (i.e. that of the alternative chain under study and the conventional chain) in favour of the alternative chain. The question that stands out here is of what factors of major variance can be optimized to reshape the distribution of the alternative chain? This question can be answered by appropriate sensitivity analysis through which the factors of major variance can be determined as done in Chapter 4 and summarized in Table 4.8. However the reshaping of the alternative chain distribution does not in all cases mean

an improvement in the average performance of the alternative chain relative to the conventional chain.

The factors of major variance in the distribution of the alternative chain are divided into two categories: (i) common factors and (ii) non-common factors. The former category refers to the factors of variance that correlate the alternative and conventional chain distributions. The reshaping of the alternative chain distribution by the optimization of a major common factor will result in the same for the conventional chain distribution and may end up increasing the overlap between the two distributions in case the variation due to the factor of interest in the distribution of the conventional chain is larger than that in the distribution of the alternative chain.

In some cases the alternative chain distribution is significantly sensitive to non-common factors of variance and the optimization of these factors may result in significant improvement in the average performance of the alternative chain relative to the conventional chain. This suggests that these alternative chains might be amenable to changes which will enhance them relative to the reference chain. In graphical terms the result is the reshaping of the alternative chain distribution towards less overlap with the conventional chain distribution. The capacity for the optimization of different types of systems through the sensitivity of the output to non-common factors of variability was discussed in Section 4.4 in Chapter 4. However in completely assessing the capacity for systems optimization one has to take into consideration not only the sensitivity of the output to the non-common factors of variability but also the sensitivity of the change distribution to the output distribution of the alternative chain and thus the size of the output variability. (Output distributions of low variability will have little impact on the change distribution.)

5.3 NG-based chains

5.3.1 Energy consumption of NG options

Figure 5.1 is a chart of the WtW energy consumption of NG-based chains together with the reference chain. The nomenclature used to describe each option is introduced in the nomenclature list. As a recap the abbreviation WtW-CGH2-NG-Central-w/CCS-FC-HEV-EC indicates Well-to-Wheel analysis of Compressed Gaseous Hydrogen from Natural Gas produced in a Central process with Carbon Capture Sequestration (CCS) and used in a Fuel Cell Hybrid

Electric Vehicle. The final EC indicates Energy Consumption. As in the rest of this chapter the box in red represents 50% of the population and acts as a graphical representation of the variance where the larger the spread of the box, the larger is the variance of the output result.

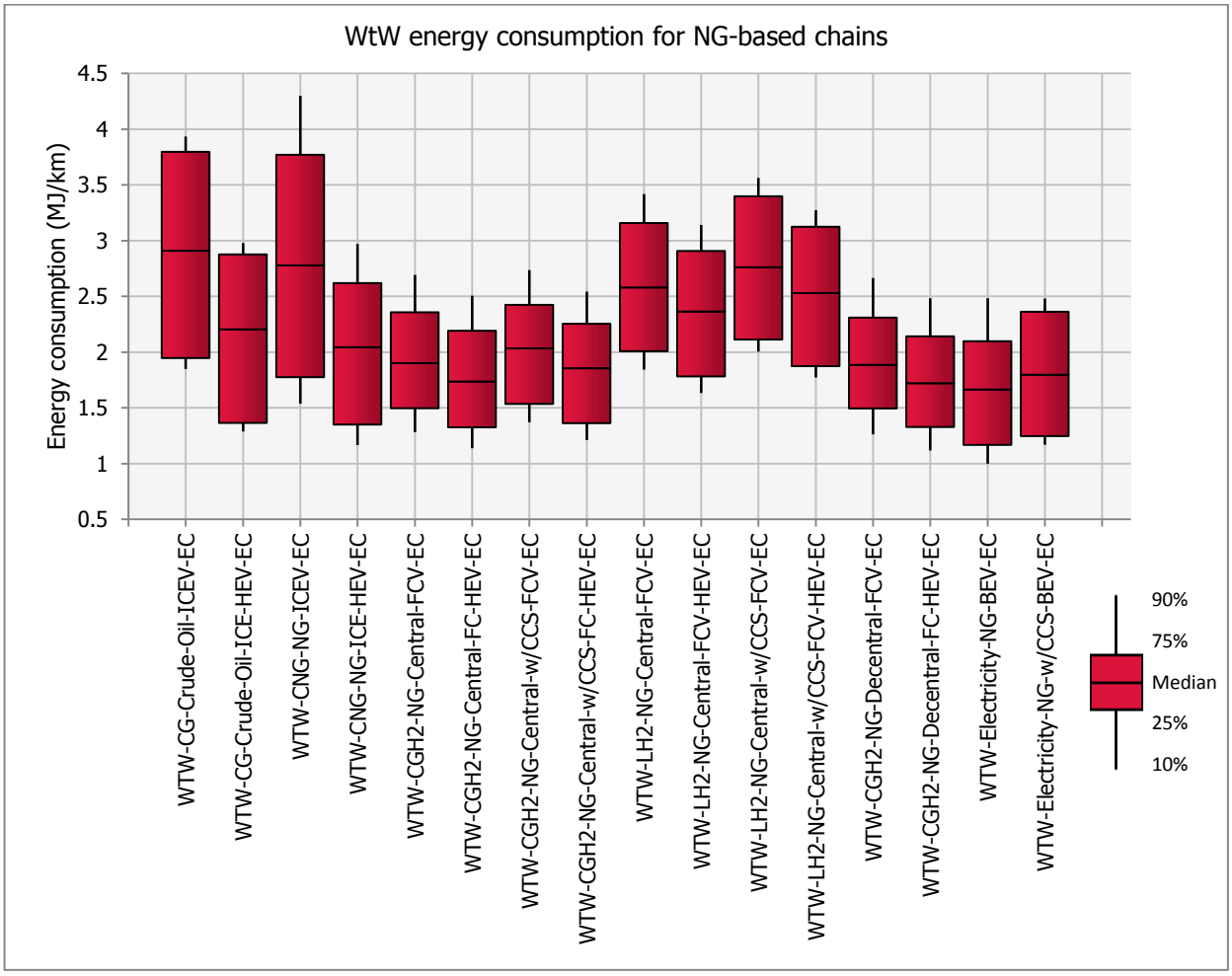


Figure 5.1: WtW energy consumption of NG-based chains together with that of two crude oil based chains including the reference chain.

Figure 5.1 can be divided into five parts. The left-hand side has the reference chain followed by this chain with the integration of hybrid electric technology. There then follows the pair for Compressed NG, after which there are four pairs of different chains each related to hydrogen, firstly in gaseous form and then as a liquid. The fourth area is the penultimate pair on the right-hand side which is for decentralized production of gaseous hydrogen. The final pair is for Battery Vehicles that has had the Electricity produced from NG; one chain has CCS, the other not. From an energy perspective, there is not a considerable benefit from the option of compressed natural gas (CNG) in a dedicated internal combustion engine vehicle. Also the reduction in energy

consumption achieved by a gasoline hybrid ICE vehicle (ICE HEV) is nearly the same as that achieved by a CNG dedicated hybrid ICE vehicle. Thus CNG does not have a clear advantage over the use of oil based chains. Gaseous hydrogen is clearly more attractive than liquid hydrogen as a result of the large energy consumption involved in liquefaction. Additional there is no noticeable differentiation between the centralized and decentralized systems of hydrogen production by steam methane reforming (SMR). Finally, a battery electric vehicle (BEV) fuelled by NG-based electricity without carbon capture (which requires a small amount of energy consumption) has a slightly better standing compared to hydrogen FC HEV.

The differential benefit of hybrid technology differs between the chains. A comparison of the first three pairs shows that the effect of hybrid technology on the standing of compressed gaseous hydrogen (CGH2) is significantly smaller than that on the standing of CNG and on the standing of the reference chain. That is attributed to two facts: (i) the effect of hybrid technology on a CNG dedicated ICEV (e.g. 20% improvement) is larger than that on a hydrogen fuel cell vehicle (FCV); and (ii) the effect of hybrid technology is an incremental reduction in energy consumption as a proportion of the WtW energy consumption of the basecase chain (the chain of the corresponding non-hybrid vehicle), whilst the WtW energy consumption of a CNG ICEV is generally significantly larger than that of a CGH2 FCV. The integration of hybrid technology not only places CNG in close competition with CGH2 but it is seen that a gasoline ICE HEV is nearly on the same standing as a CNG ICE HEV.

5.3.2 Energy change distributions for the NG options

Although the median provides a valuable general indicator, an analysis based on median values does not reflect the whole population. Statistically sound comparisons between options can be made by taking a closer look on the standing of each alternative option. The vertical lines in Figure 5.2 are delimiters which split the population for each distribution into three parts. The below zero proportion of the whole population is very important as it represents the size of the risk of energy debt, i.e., of there not being energy savings, which was labelled the Risk Zone. The below -1.0 MJ/km proportion of the population represent the opportunity of large energy savings (A change of -1.0 MJ/km was chosen to represent a level whose magnitude might be considered large and this was labelled the Opportunity Zone). The in between population is also

one of energy savings. For each option a measure of the Opportunity Zone and the Risk Zone has been obtained and these are tabulated at the top of Figure 5.2.

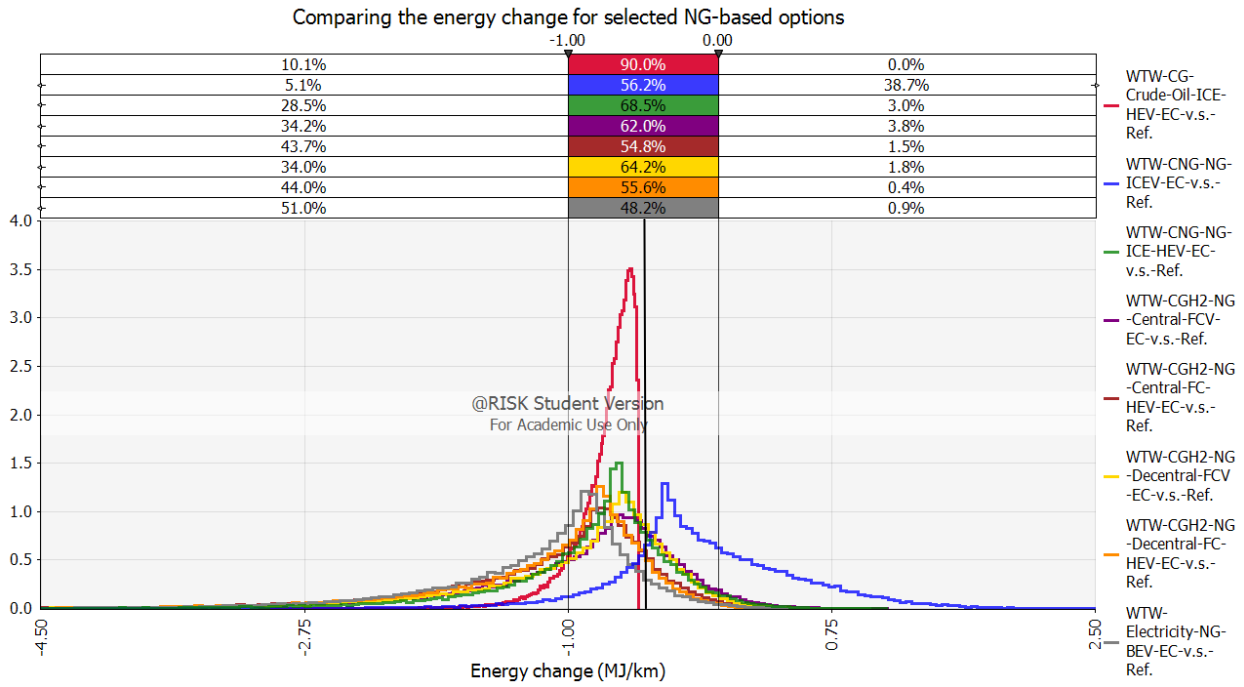


Figure 5.2: The energy change distributions relative to the reference chain for various NG-based options. The emerging hybrid gasoline vehicle option is also included.

Interestingly none of the options presented in Figure 5.2, apart from the gasoline ICE HEV, is completely without risk. The only option that provides definite energy savings is the integration of hybrid technology to the reference system with zero probability in the Risk Zone. The variability in the energy change distribution for the gasoline ICE HEV chain, with respect to the standard gasoline ICEV chain, as represented by the red distribution in Figure 5.2 is mainly a result of the difference in the variance between the two subtracted distributions (the energy consumption of the reference chain and that of the gasoline ICE HEV). In this case the subtracted distributions move in perfect tandem in the sense that a proportional change in the performance of the non-hybrid vehicle option (e.g. 10% improvement in energy consumption with time) is matched with an equal proportional change in the performance of the corresponding hybrid vehicle option, yet the difference between the two distributions is variable because the hybrid option by convention performs better than the corresponding non-hybrid option in the base case. From the above analysis one can directly rule out the option of CNG ICEV which has considerable probability of resulting in an energy debt rather than an energy credit. As seen in

Figure 5.2, 39% of the population is in the Risk Zone. However, one cannot rule out the remaining options including CNG ICE HEV which have almost negligible chances of becoming energy debtors and significant chances (29% to 51%) of providing large energy savings ≥ 1.00 MJ/km.

Again one can see the effect of hybrid technology on the standing of CNG as an alternative fuel. The CNG ICE HEV, CGH2 FCV/FC HEV, and BEV options have good chances of performing better than gasoline ICE HEV in terms of energy savings. Unlike the gasoline ICE HEV which has a small population (10%) in the defined Opportunity Zone (≥ 1.0 MJ/km of energy savings), the FCVs and BEV have significant populations of energy savings ≥ 1.0 MJ/km as quoted earlier and shown in Figure 5.2. However, the gasoline ICE HEV has the advantage that its savings are more secure with there being no chance of it becoming an energy debtor and with guarantees of significant energy savings. The author notes in passing a question that policy planners will have to address. The question is whether to eliminate risk and guarantee limited energy savings or seek to achieve greater but riskier savings?

Now in the case of hydrogen FCVs and NG-based electricity fuelled BEV one have more capacity to decrease the variance of energy consumption and reshape the change distribution to ensure significant energy savings by assuming (i) high SMR energy balance (maximum efficiency) and low hydrogen compression energy in the case of CGH2 FCV/FC HEV, and (ii) high efficiency Combined Cycle Gas Turbine (CCGT) power plant in the case of NG-electricity fuelled BEV. Thus by interference one can place hydrogen fuelled and electricity driven vehicles on the safe side together with gasoline in ICE HEV.

5.3.3 GHG emissions of NG options

Apart from the chains with CCS, the picture for GHG emissions (Figure 5.3) seems similar to that for energy consumption (Figure 5.1) albeit most of the chains show less variance. This is because the GHG emissions associated with most of the vehicles (including for example CGH2, FCV and BEV) have no emissions and hence have zero variability for the last part of the chain. On closer inspection it is seen that there is less overlap with the distribution of the reference chain.

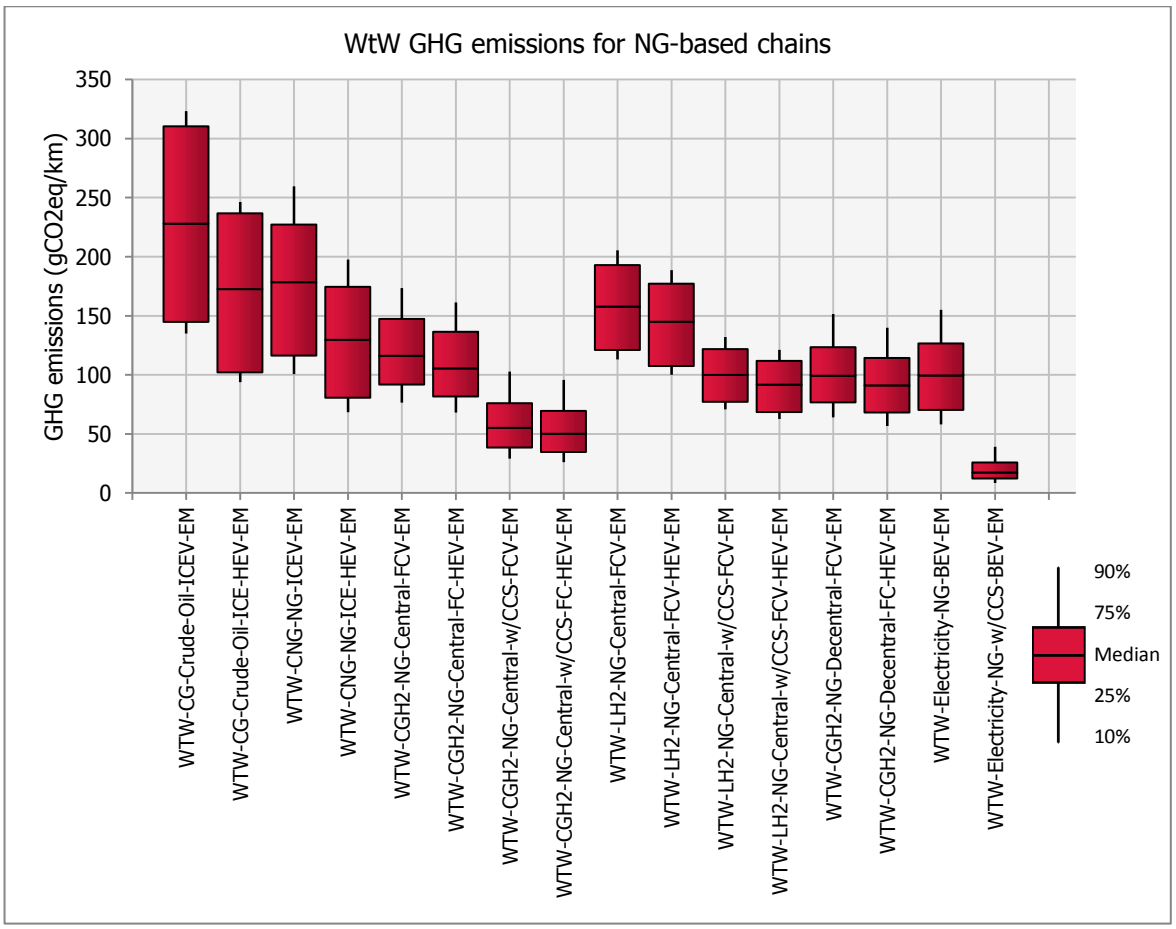


Figure 5.3: The WtW GHG emissions for NG-based chains. Two crude oil based chains including the reference chain are also included.

As there is generally less overlap in Figure 5.3, then the changes shown in Figure 5.4 indicate, in the case of GHG emissions, an improvement in the standing of CNG ICEV with lower risk of GHG debt as compared to the reference chain. For others, the larger population of GHG emissions in the Opportunity Zone make them more attractive; for CNG ICE HEV, CGH2 FCV, CGH2 FC HEV and BEV options, 35% to 54% of the population is in the defined Opportunity

Zone (≥ 100 gCO_2eq/km of savings). Overall, the risk associated with the GHG emissions changes of the CNG ICEV is large enough to disqualify this option from the list of prospective alternatives.

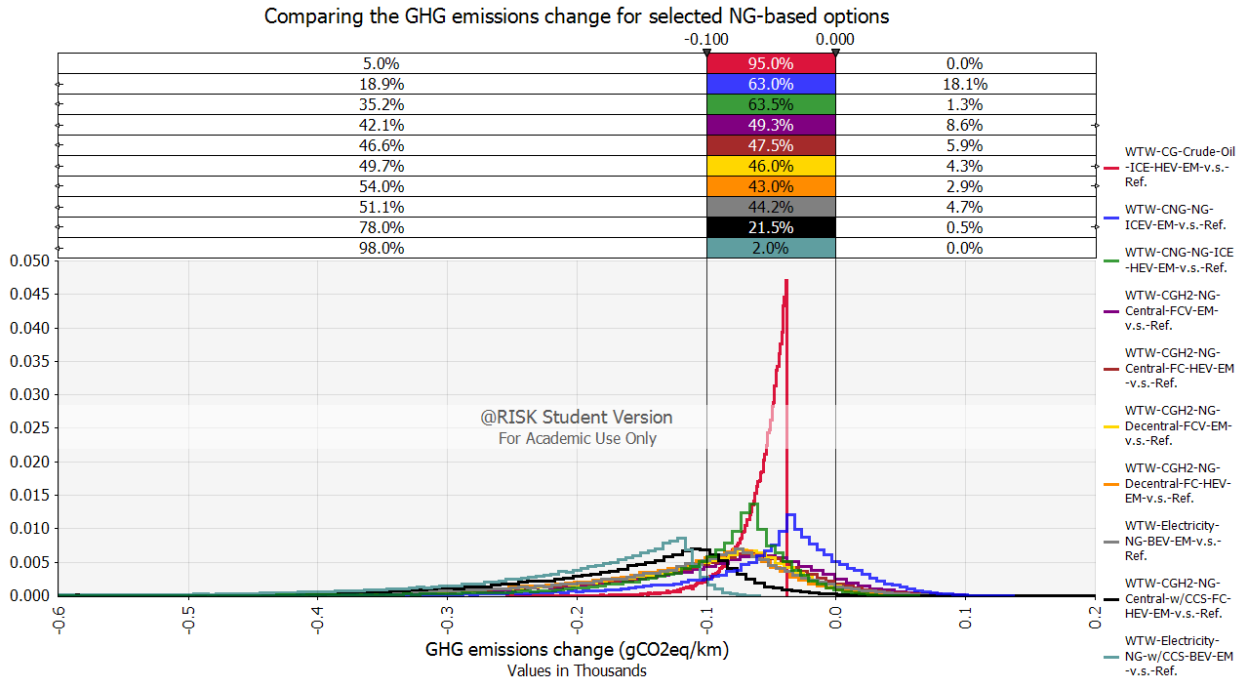


Figure 5.4: The GHG emissions change distributions relative to the reference chain for various NG-based options. The emerging hybrid gasoline vehicle option is also included.

On the other hand, the integration of carbon capture and sequestration (CCS) technology is very attractive and places CGH_2 from central reforming and NG-based electricity at the forefront of the alternative options to curb carbon emissions in transport. As seen in Figure 5.4, 78% to 98% of the GHG emissions change population of the options presented with carbon capture are in the defined Opportunity Zone (≥ 100 gCO_2eq/km of savings). In fact, the carbon capture technology brings on average an extra GHG emissions savings of 61 g of CO_2eq/km with CGH2 (central) FCV and 82 g of CO_2eq/km with NG-based electricity BEV. Although these numbers are very attractive there remains, of course, the matters of cost and feasibility of CCS technology.

5.4 Non-biomass renewables

The non-biomass renewable resources under consideration include solar, wind, hydro and geothermal. For passenger transport these different resources need to be harnessed to generate electricity for either direct use in a BEV or for hydrogen production (via water electrolysis) to

give the fuel for a FCV. Thus the energy account of non biomass renewables starts after conversion into electricity.

5.4.1 An overview of the energy consumption

Figure 5.5 below includes the reference chain and three pairs of options for hydrogen production and one for the BEV.

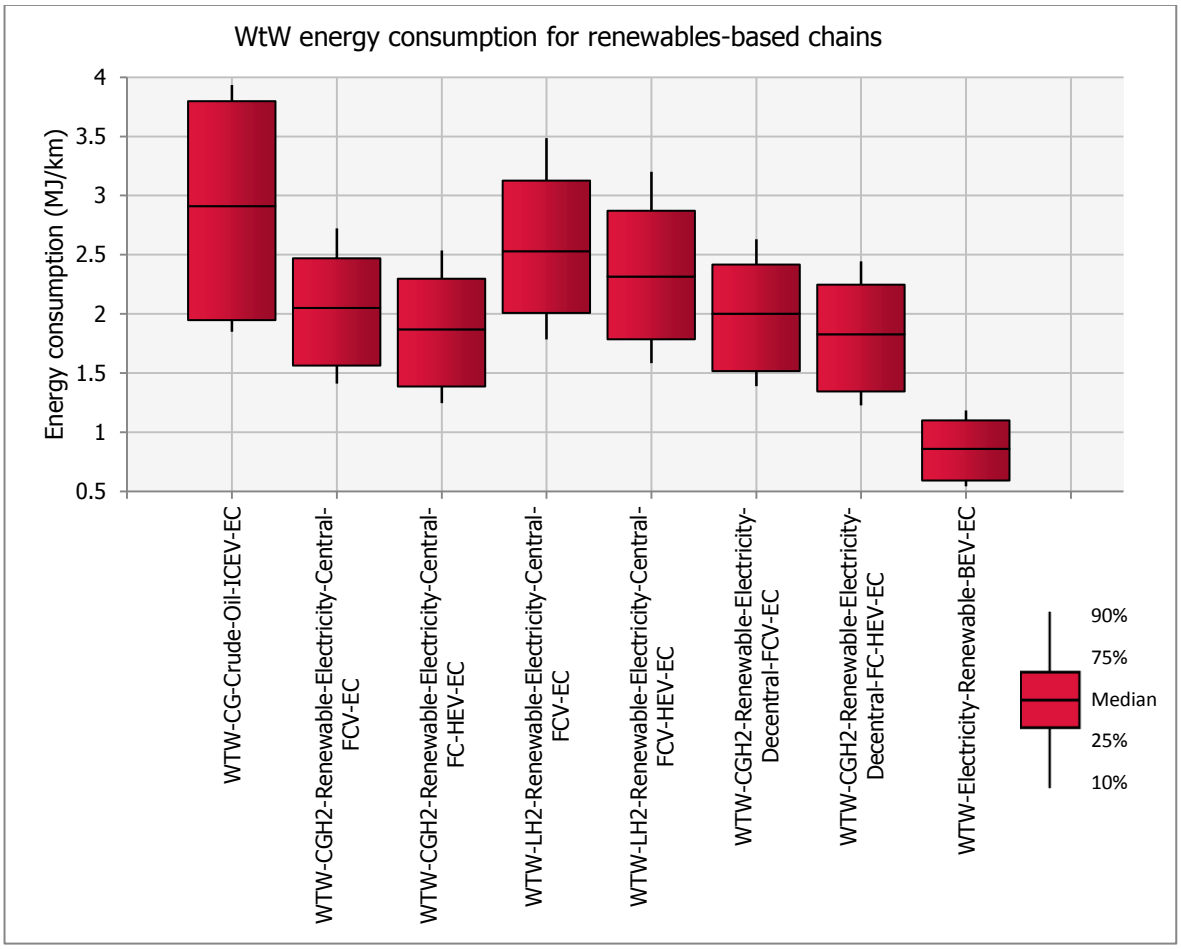


Figure 5.5: The WtW energy consumption for various chains fuelled by renewable generated electricity together with the reference chain

Clearly liquid hydrogen is an unattractive option, whilst there is little to distinguish the centralized generation of gaseous hydrogen from the decentralized generation of the same fuel. However the renewables fuelled BEV option stands out from amongst the other renewables-based options as presenting distinctively high energy efficiency. A closer look on the energy consumption of different renewables based chains is shown in Figure 5.6.

5.4.2 A closer look on energy consumption

The stand-out result of Figure 5.6 reconfirms what was seen earlier in Figure 5.5 concerning the BEV option with 90% of the energy consumption population ≤ 1.18 MJ/km while all renewable based hydrogen FCVs have almost negligible populations in this opportunity range. Also one can see that liquid hydrogen is an unattractive option with 25% to 37% of the energy consumption ≥ 2.87 MJ/km. The clear difference between the distributions of the hydrogen options and the energy distribution of the BEV option in Figure 5.6 below is mainly a result of (i) the higher efficiency of BEV over FCV and (ii) the energy lost in the electrolysis process.

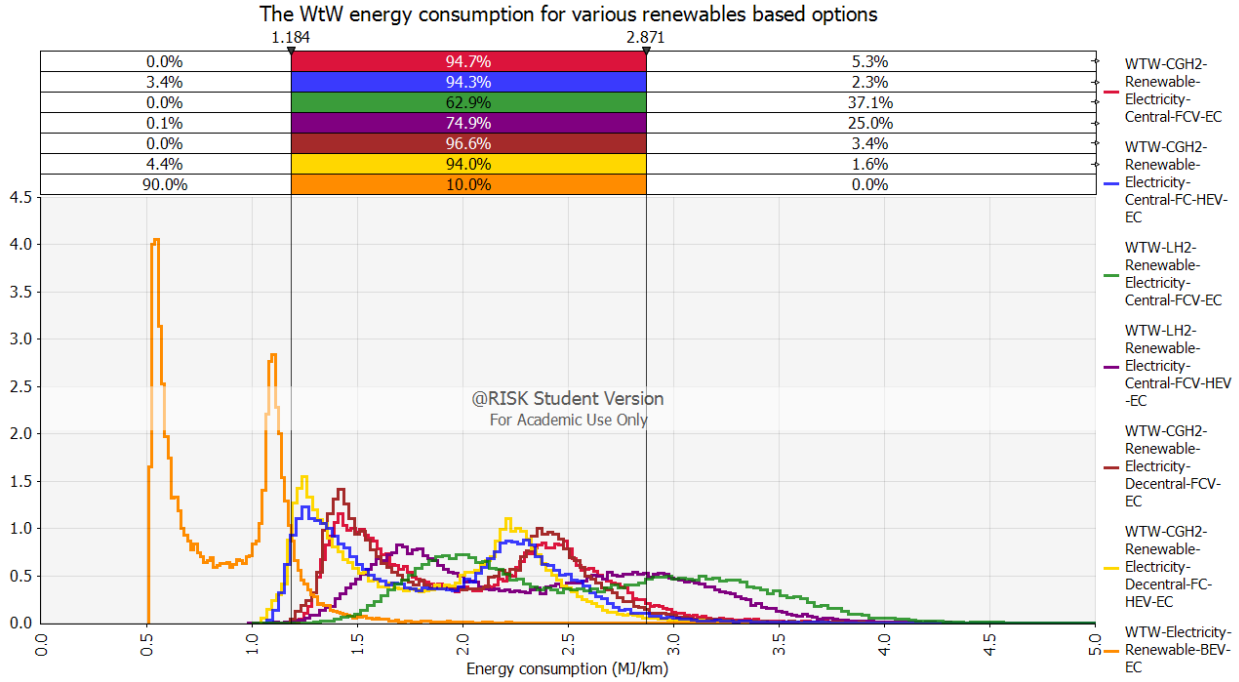


Figure 5.6: The energy consumption distributions of various renewables-based options

Nevertheless some may claim that hydrogen is necessary for electricity storage due to the intermittent nature of renewable resources. The energy loss for the storage of renewable electricity in hydrogen and supply ranges from 45 to 57%[13] compared to only 7% for renewable electricity supply through the grid. How can one justify an energy loss of 38 to 50% for storage? Some researchers such as Converse (2006) have concluded that the low cost of hydrogen storage

[13] Assuming 100% of the energy lost is renewable electricity. The lower bound of the range is the median energy consumption of the renewable CGH2 (central) WtT chain and the upper bound is the median energy consumption of the renewable LH2 WtT chain.

compared to the high cost of other electricity storage systems could be the factor which justifies the choice of hydrogen as the energy carrier (see Table 5.1 below).

	Capital cost $/KWh stored	Efficiency (%)
Pumped hydro	16.8	75/87
Secondary battery	200	75/87
Lead acid	150-200	
Flow batteries	125-1000	75-85/90
Fly wheels	800	90
Underground storage of compressed air with expansion through a gas turbine	10	70 + fuel
Compressed air in vessels	250	60 + fuel
Underground storage of compressed hydrogen	0.29	51/60

Table 5.1: Capital cost of electricity storage (Converse, 2006)

This may look true today given the small scale of renewable electricity production; wherein the production systems are not well distributed. However, in the case of large scale renewable electricity production the integration of renewable electricity systems becomes practically convenient and would be the ideal solution for overcoming the intermittence barrier. As such, there is no absolute justification for the use of hydrogen as a means for renewable electricity storage and losing approximately 38 to 50% of the energy in hand.

5.4.3 GHG emissions of renewables based options

The general picture for GHG emissions can be seen in Figure 5.7 and Figure 5.8. In terms of GHG emissions savings all the options are very similar. Nearly all of the populations of GHG emissions change (95% to 100%) are in the defined Opportunity Zone ($\geq$ 100 gCO_2eq/km of GHG emissions savings). This is because both FCVs and BEVs are green vehicles which generate zero GHG emissions and the electrolysis process which is part of the hydrogen chains but not the electric chain generates zero *direct* GHG emissions. The only notable difference between the BEV option and the hydrogen options as seen in Figure 5.8 below is at the upper tail and is due to the *indirect* GHG emissions associated with the supply of electricity lost in the electrolyzer.

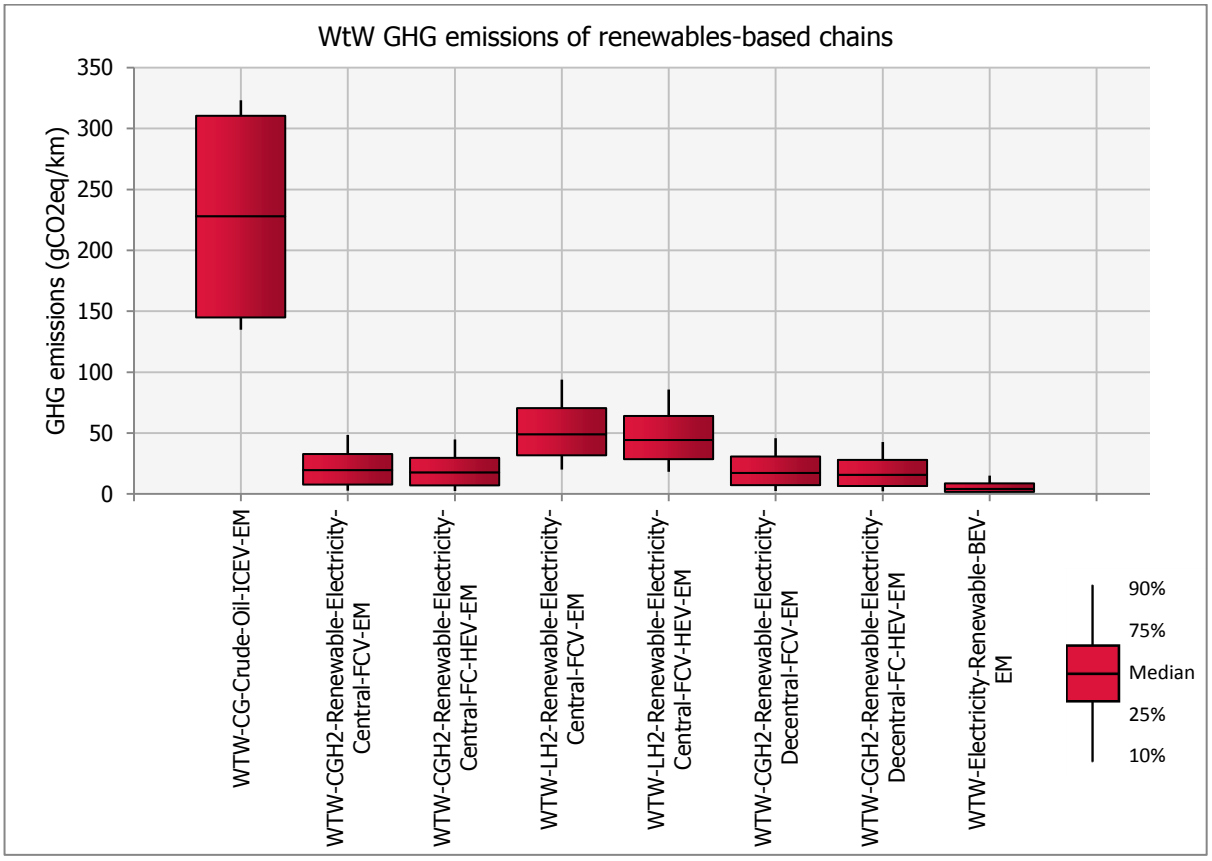


Figure 5.7: The WtW GHG emissions of non-biomass renewables based chains

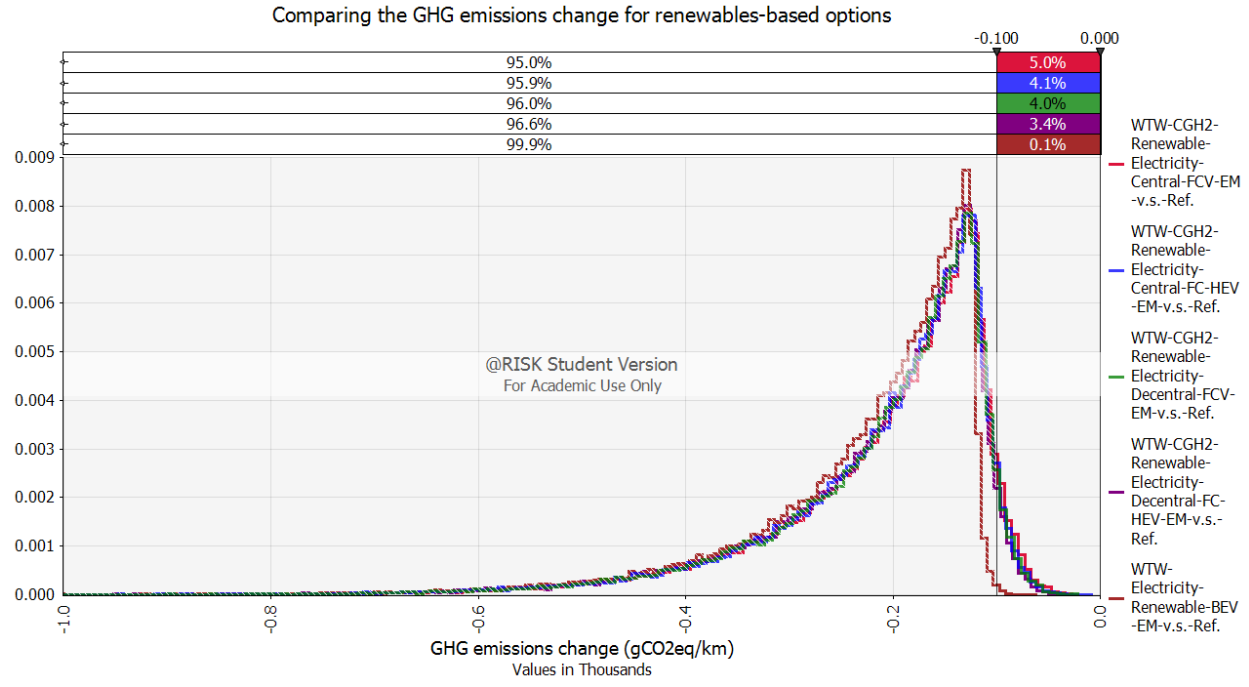


Figure 5.8: The GHG emissions change distributions for selected renewables-based options

5.5 Nuclear-based chains

As seen in Figure 5.9 below the nuclear-based hydrogen options are not attractive in terms of energy sustainability. On the other hand, the nuclear electricity BEV option is significantly better. Nevertheless, in terms of energy consumption all of the options presented in Figure 5.9 overlap with the reference chain. The distribution of expected energy changes is given in Figure 5.10. It is seen that the nuclear-based hydrogen options are unattractive with 87% to 91% of the energy change population in the Risk Zone. On the other hand, the risk associated with the nuclear electricity BEV option may be acceptable with 86.2% of the change population is below zero, i.e. savings are expected.

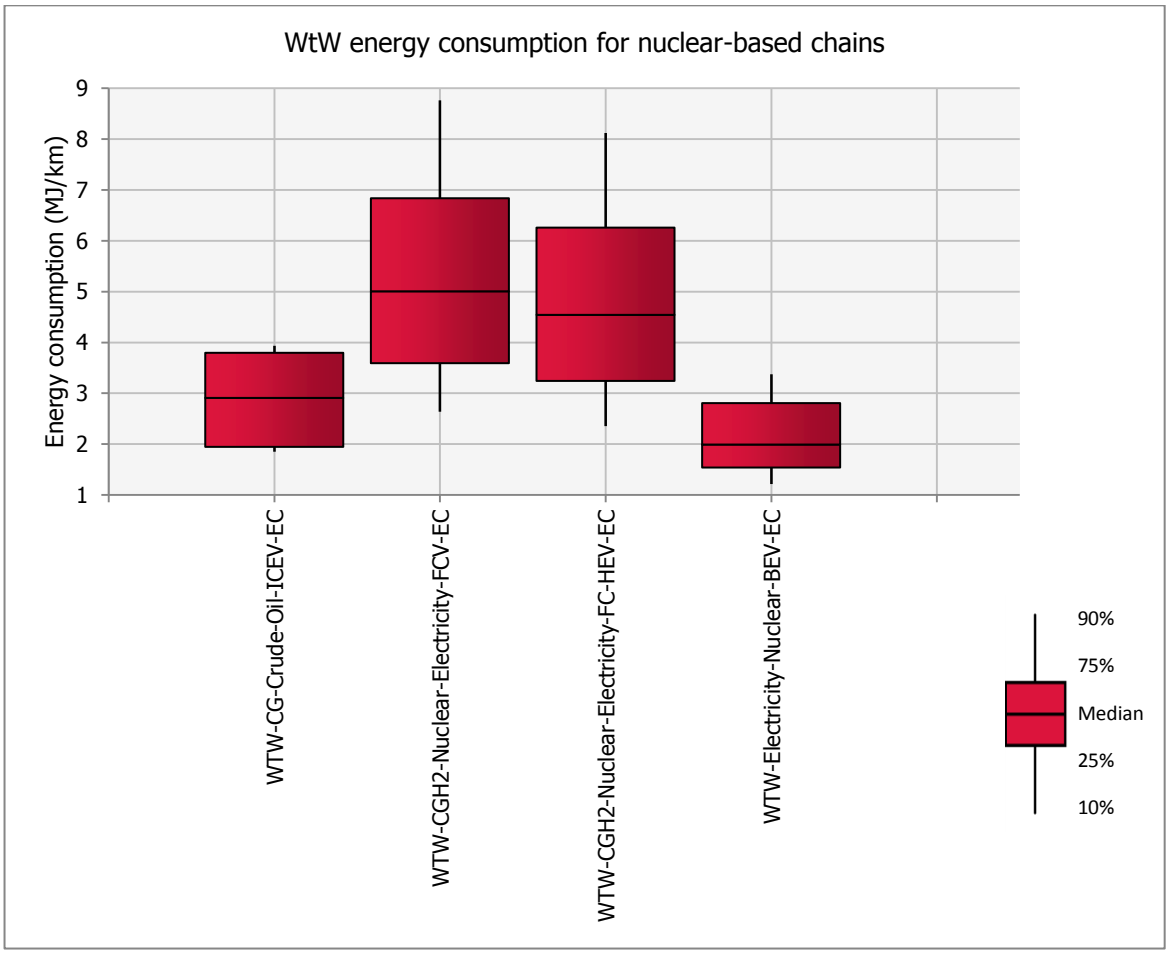


Figure 5.9: The WtW energy consumption for nuclear-based chains

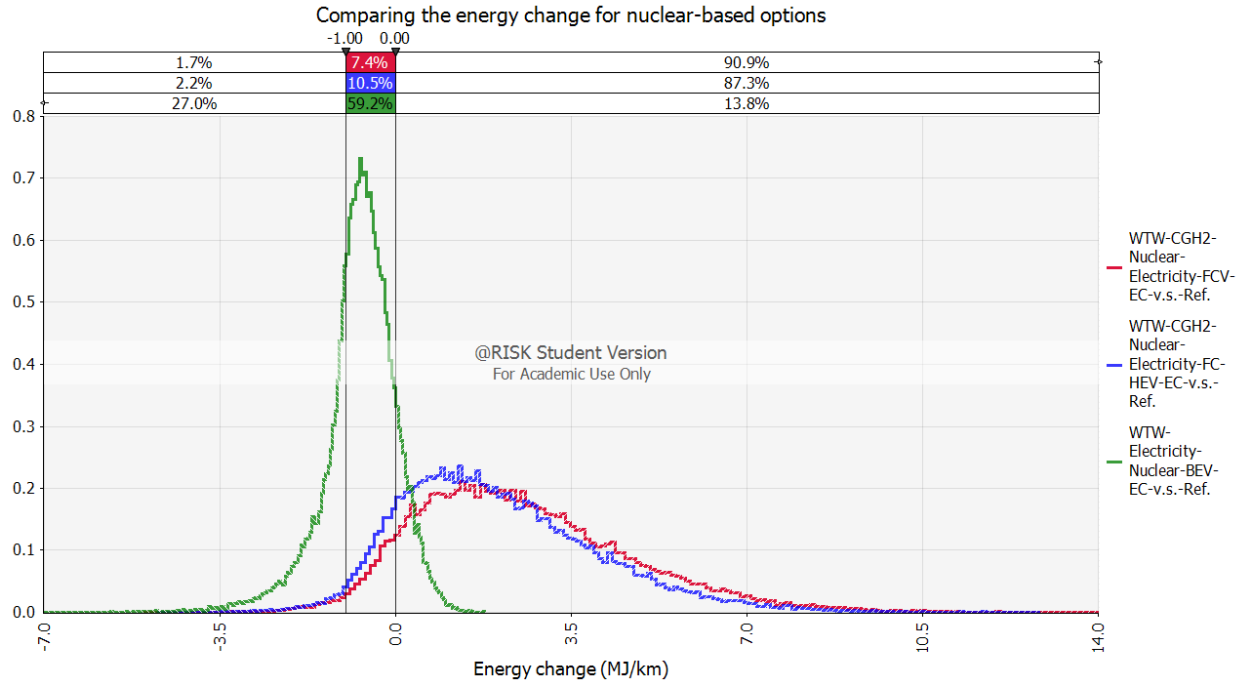


Figure 5.10: The energy change distributions for nuclear-based chains relative to the reference chain

Figure 5.11 and Figure 5.12 below give the WtW GHG emissions of the nuclear based chains. The nuclear-based transport chains in general and the nuclear electricity BEV chain in particular offer large GHG savings.

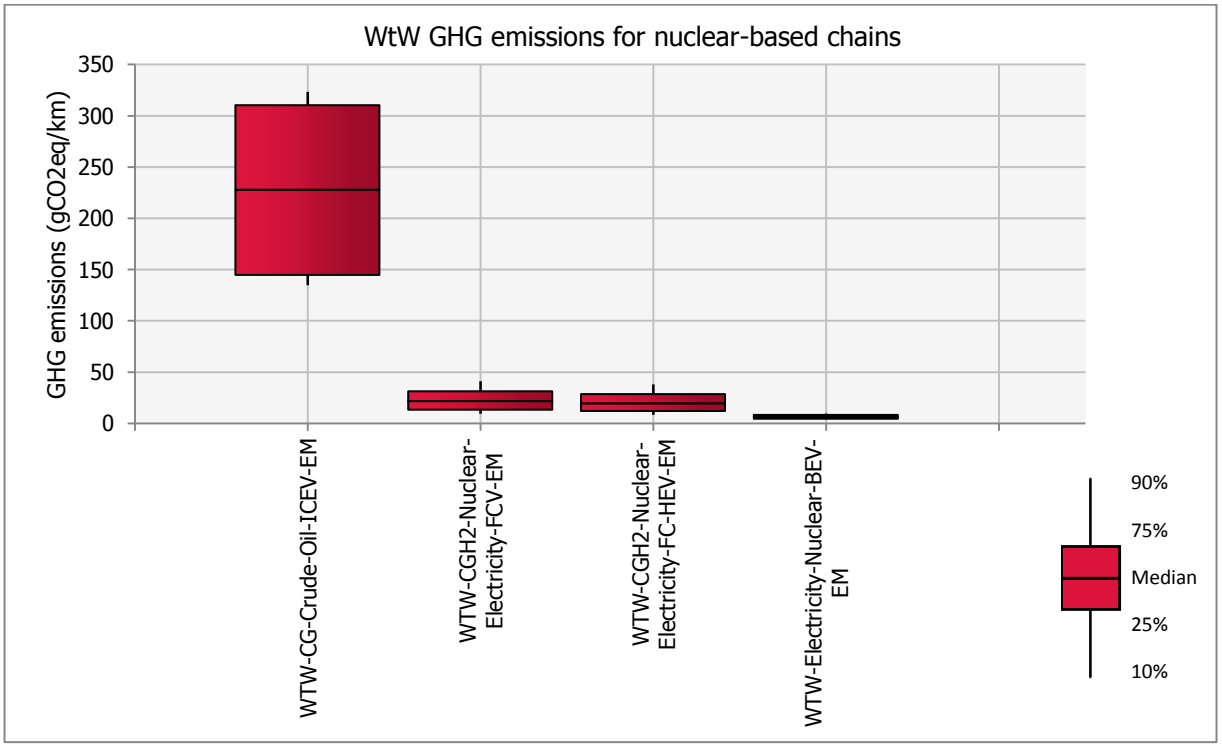


Figure 5.11: The WtW GHG emissions for nuclear-based chains

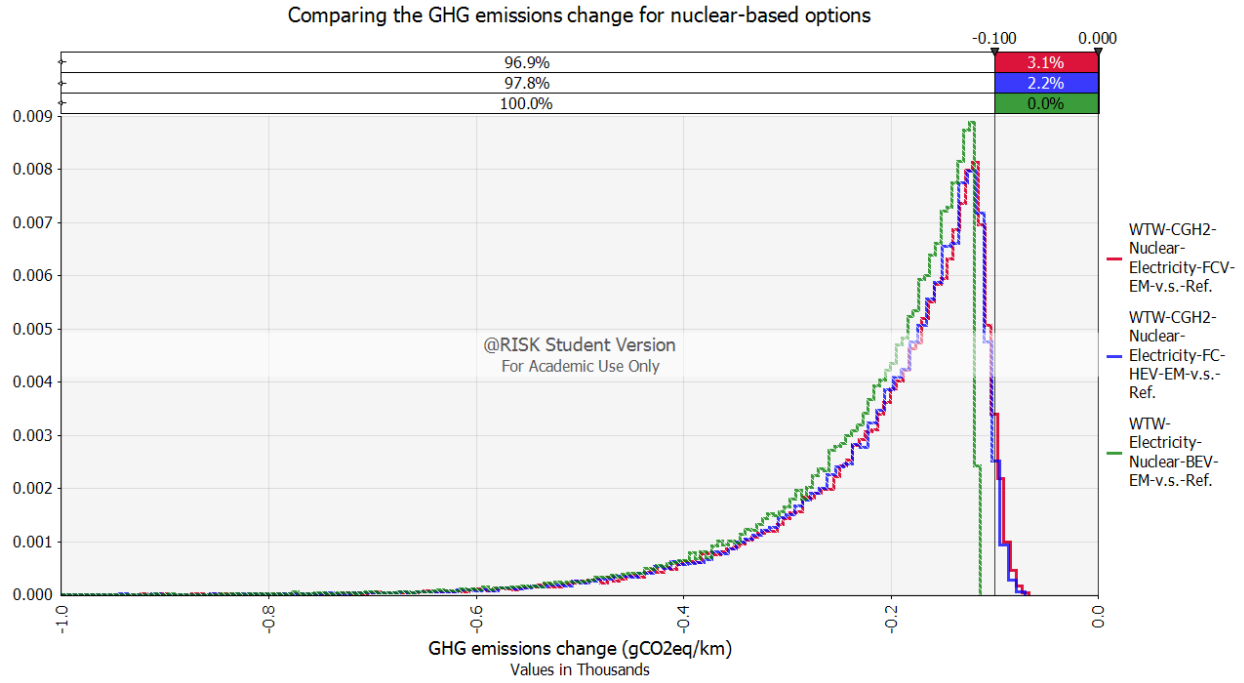


Figure 5.12: The GHG emissions change distributions for nuclear-based options

5.6 Coal-based chains

In order to assess the effect of introducing battery electric vehicles into the transport sector in the short to medium term it is necessary to include BEVs driven by coal-based electricity. This option is compared with the conventional reference chain.

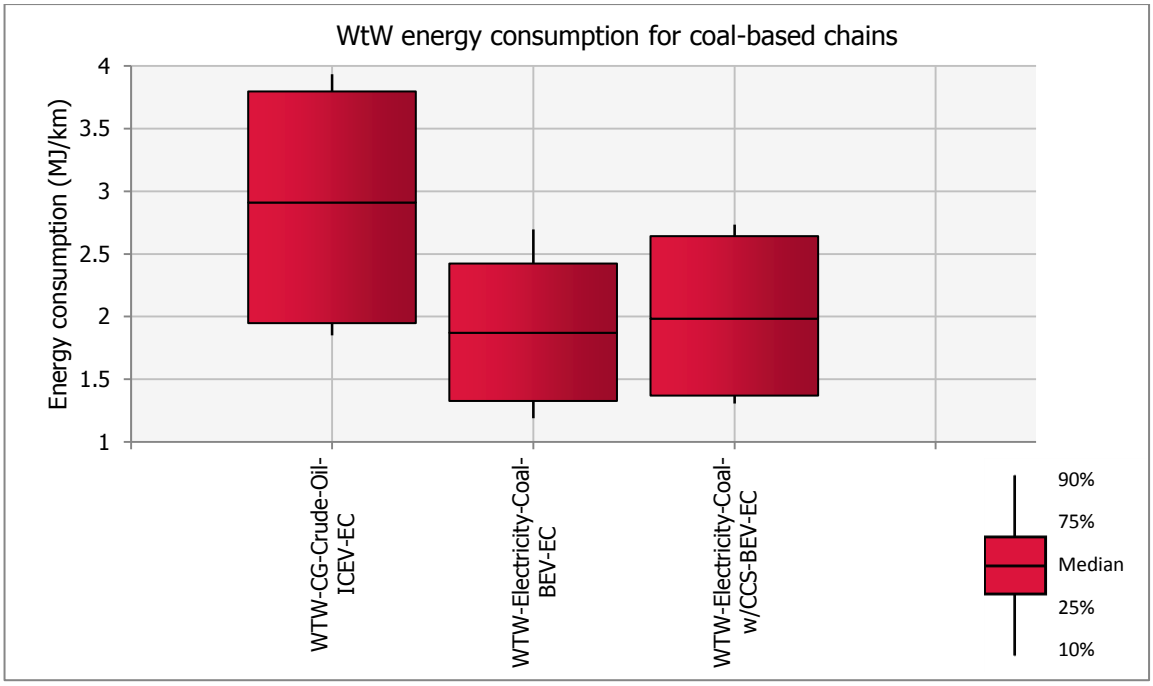


Figure 5.13: The WtW energy consumption for coal-based chains together with the reference chain

Figure 5.13 presents the energy consumption of coal-based electricity on WtW basis; the measures overlap and thus a closer look on the energy savings is made in Figure 5.14. The coal-based electricity option presents no significant risk of energy debt; on the contrary it presents significant chances (37%) of energy savings ≥ 1.00 MJ per kilometre. Furthermore through the choice of high efficiency integrated gasification combined cycle technology (IGCC) or what is commonly known today as the clean coal technology for electricity production the above distribution can be re-shaped to eliminate the tiny risk of being above zero. Furthermore GHG emissions move in the right direction.

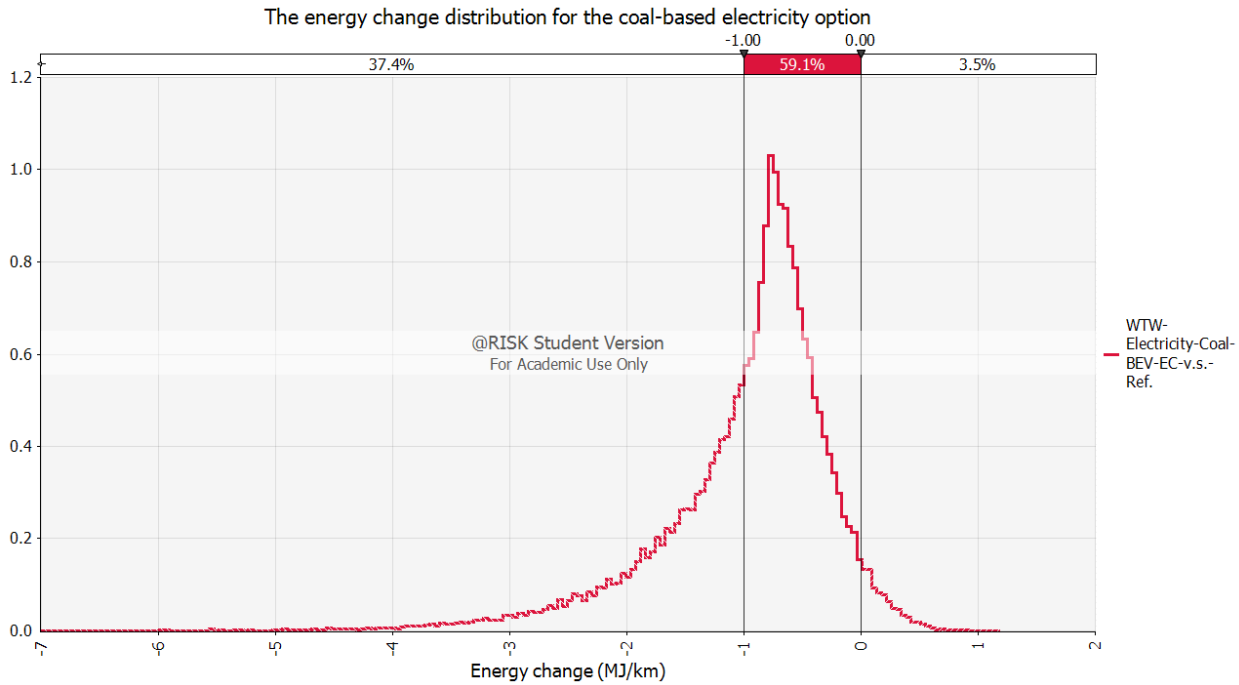


Figure 5.14: The energy change distribution for the coal-based electricity option relative to the reference chain

In terms of GHG emissions the coal-based electricity option overlaps more with the reference chain than it did for energy consumption (Figure 5.13). However as seen in Figure 5.15, the potential of GHG emissions savings is there with coal-based electricity with carbon capture and sequestration (CCS) technology.

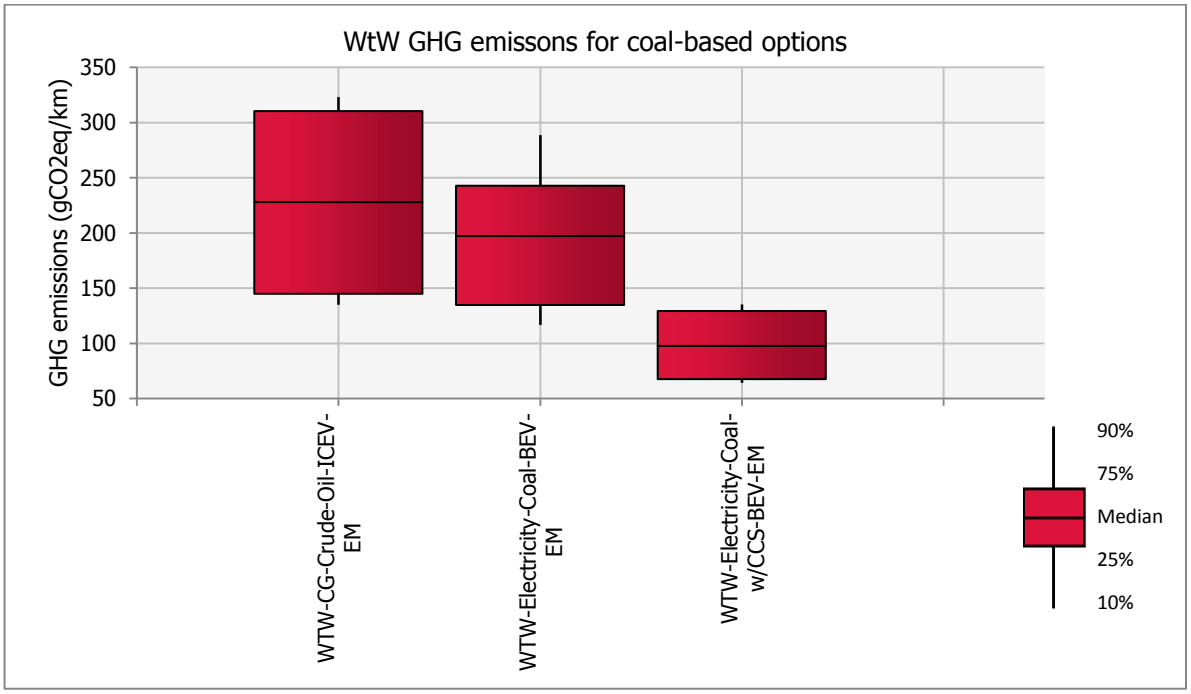


Figure 5.15: The WtW GHG emissions for coal-based chains

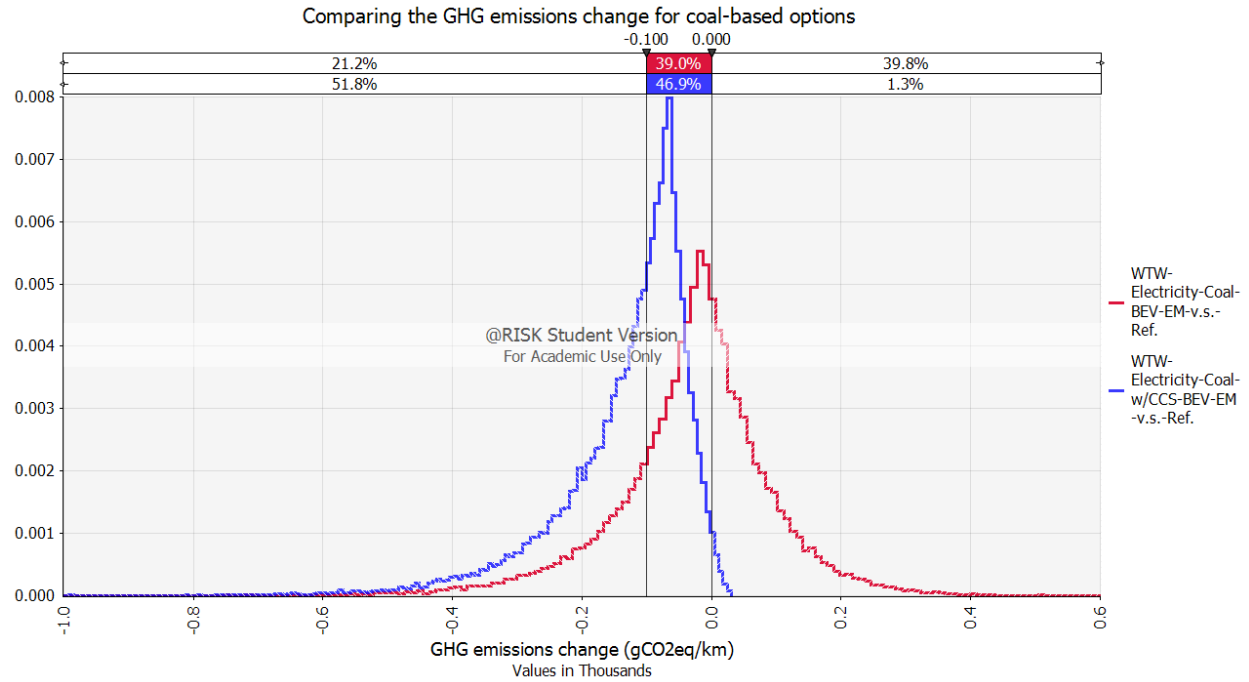


Figure 5.16: The GHG emissions change distributions for coal-based options

Figure 5.16 indicates the risk of GHG emissions debt that is associated with the option of coal-based electricity without CCS technology; it is relatively large with 40% of the population in the Risk Zone. Only with the integration of CCS technology can one almost guarantee no GHG

emissions debt. Moreover, with the clean coal technology (IGCC) in addition to the CCS technology the guaranteed savings is still not significant.

5.7 Biomass-based chains

There are three main routes for biomass use in the transport sector: (i) the conversion of biomass to gaseous hydrogen by gasification and its use in a fuel cell vehicle, (ii) the conversion of biomass to ethanol by fermentation and use in an ICEV or alternatively in a FCV (with integrated fuel processing) and (iii) the conversion of biomass to biodiesel. The type of ICEV considered in the current study is ethanol dedicated; the ethanol FCV is a second generation vehicle technology.

5.7.1 Land use efficiency

In Section 5.1 the criteria of comparison between the different options under study including options based on renewable or non-exhaustible resources was discussed. The biomass feedstock is reproduced in cycles on land and thus is a non-exhaustible resource. As such the energy efficiency has no important implications when comparing chains that are based on different types of biomass (wood, sugarcane, etc).

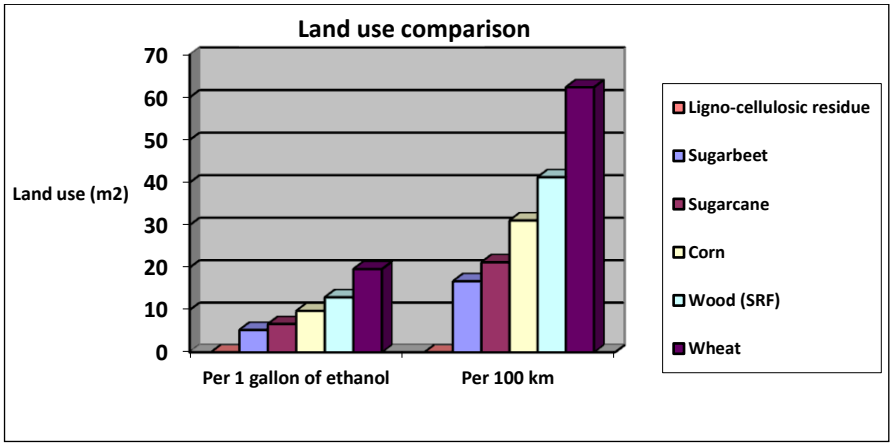


Figure 5.17[14]: The land use of different types of biomass feedstock for bioethanol production per (i) 1 U.S gallon of ethanol in vehicle tank, and (ii) 100 km

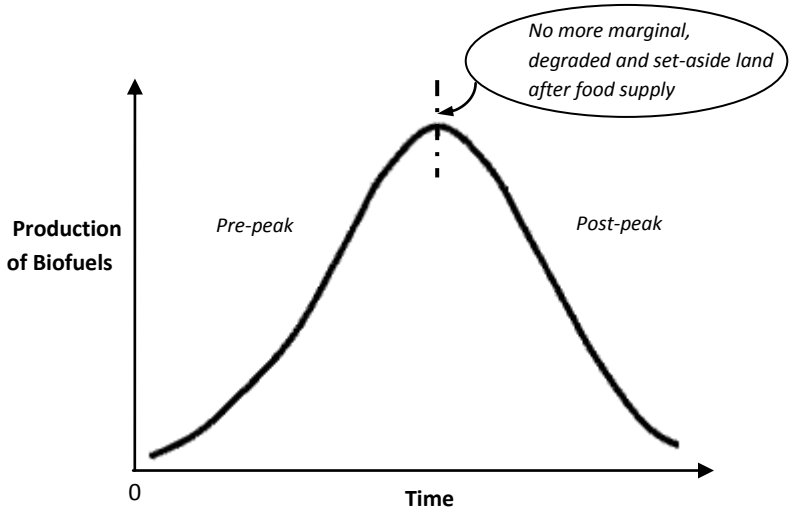
[14] Data for the land use assessment on WtT basis is adopted from the GREET and JRC databases; data for the calculation of the average performance of ethanol dedicated ICEV is adopted from the JRC, GREET and LEM databases (3.2 U.S gallons of ethanol per 100 km).

In fact the most important factor in the comparison of different biomass based chains is the land use efficiency and the competition with food markets. Nevertheless, across the chains that are based on different types of biomass the land use efficiency does not necessarily move in tandem with the energy efficiency. This suggests that the land use efficiency should be separately accounted for in the analysis and this was done by performing a preliminary land use assessment for selected types of biomass for bioethanol production. The results of the land use assessment are shown in Figure 5.17 above as copied from Figure 4.4 in Chapter 4 (references presented in the footnote).

While one can see in Figure 5.19 that the sugarcane options present the worst energy efficiency, on the other hand they are among the best options in terms of land use efficiency as seen in Figure 5.17 above. This can be attributed to the fact that land use is largely associated with the farming yield per hectare while the WtW energy consumption is only loosely associated with the farming yield per hectare through the energy requirement for fertilizers supply and farming practices (e.g. tillage).

The importance of the land use dimension in the analysis was emphasized earlier in Chapter 4 where the preliminary assessment of land use for bioethanol production was performed. The introduction of biofuels in the transport sector only makes sense if it does not jeopardize the food supply market. In this section the significant implications of land use efficiency are further discussed.

Figure 5.18: The complete cycle of biofuels production



Assuming the best management practices by (i) not allowing deforestation and (ii) giving priority to food production, it will be seen that it is only a matter of time before the demand for biofuels start competing with the demand for food. On one hand, the diversification of primary crops use by opening a market for wheat/corn ethanol implies immediate competition between the demand for food and the demand for biofuels; moreover, such a move will escalate in less time to a food crisis as the land use for wheat/corn ethanol production and use in the transport sector can be very inefficient as presented in Figure 5.17. On the other hand, the plantation of alternatives such as sugarcane, sugarbeet and poplar wood on marginal, degraded and set-aside land for biofuels production will only delay the competition between the demand for food and the demand for biofuels until land becomes scarce and the two markets have to compete with each other.

As depicted in Figure 5.18 one can envisage that the production of biofuels from cultivated biomass peaks at some point and follows the bell-shaped curve of oil production named after the American geologist M. King Hubbert as the Hubbert's curve (Hubbert, 1956). Early in the curve (pre-peak) the production of biofuels increases with the increase in demand using the marginal, degraded and set-aside land that is spared by food production. The peak represents the point when there is no more spare land after food production. Late in the curve (post-peak) the production of biofuels decreases to free-up land for the ever increasing food demand. The efficiency of land use in the transport sector plays a major role in shaping the curve by affecting the time lag before the peak in biofuels production is reached. To summarize: *Cultivated biomass is an available option in the mean time but not a sustainable option on the long run*.

As seen in Figure 5.17, among the different types of cultivated biomass under consideration in the current study, sugarbeet performs the best in terms of land use. However, sugarbeet ethanol in the transportation sector is not among the options that can be commercialized today such as sugarcane ethanol in Brazil and corn ethanol in the U.S (Peña, 2008). Further study should be done on the economic feasibility of sugarbeet ethanol in Europe and its potential for short term penetration into the transport sector. On the other hand, the option of sugarcane ethanol is already commercial in Brazil and performs among the best cultivated biomass based options in terms of land use efficiency.

Nevertheless, in this respect the non-cultivated type of biomass such as waste wood and corn stover is the most promising feedstock for biofuels production because no land use is associated.

In particular, waste wood feedstock is most attractive because in addition to avoiding land use it is not used as animal feed and thus does not interfere with the animal feed market (there is no need to find an alternative animal feed as in the case of using wheat straw for biofuels production).

5.7.2 Energy consumption of biomass options

As seen in Figure 5.19 the production of ethanol from different types of biomass and its use in the transport sector through first generation bio-vehicles (i.e. ICEVs) is on average much less energy efficient than both the conventional chain as well as the biomass based hydrogen chains.

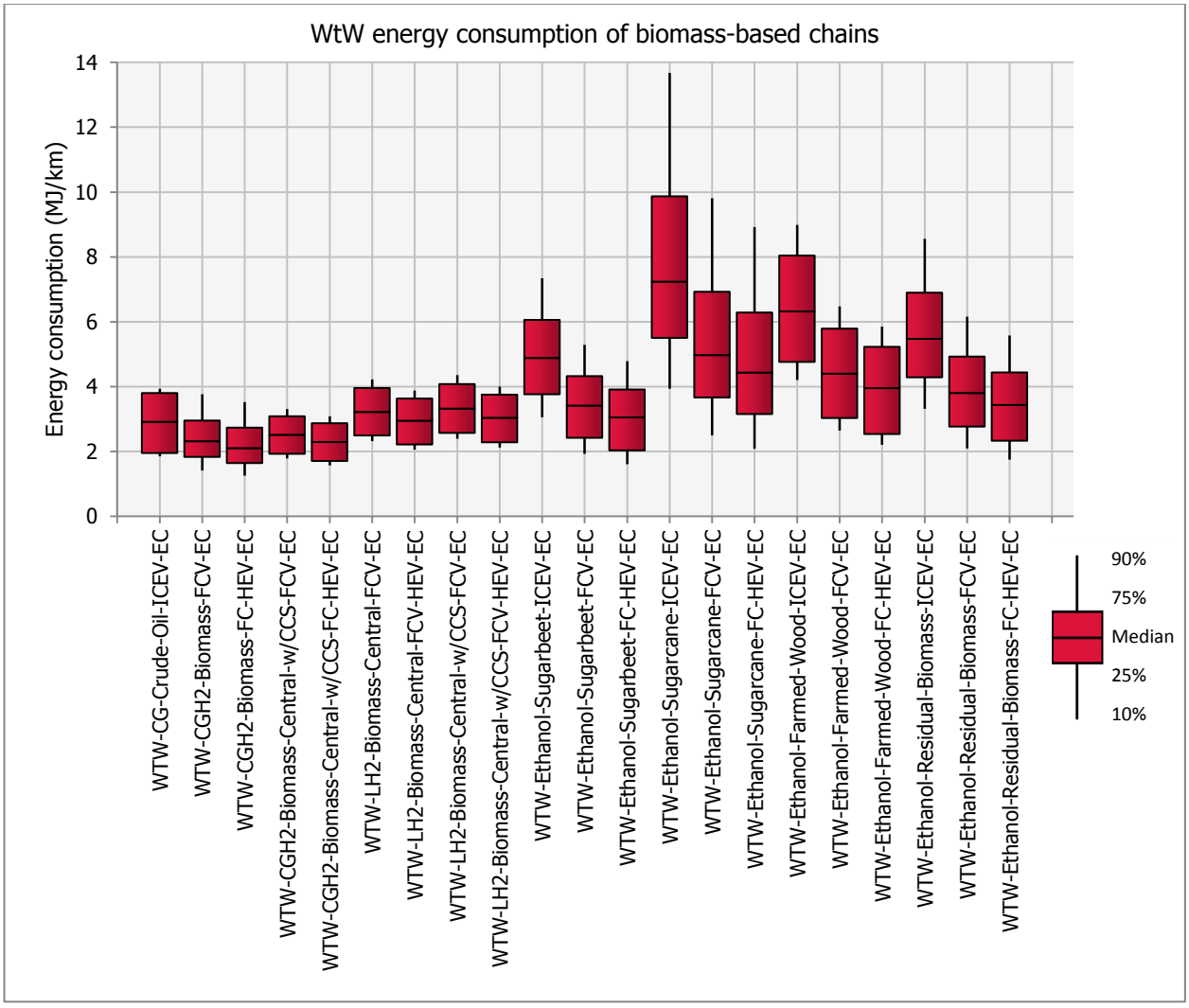


Figure 5.19: The WtW energy consumption of biomass-based chains

The high profile energy use of ethanol chains as compared to the conventional chain is mainly attributable to the large amounts of energy use in the fermentation process. The difference with

respect to the biomass-based hydrogen chains is mainly attributable to the increase in the energy use for biomass processing (between the gasification and fermentation processes) and the large decrease in the vehicle efficiency (between the CGH2 FCV and the ethanol ICEV). In the following analysis a closer look is taken on the standing of the ethanol chains as well as the biomass-based hydrogen chains in terms of energy efficiency and the implications are discussed.

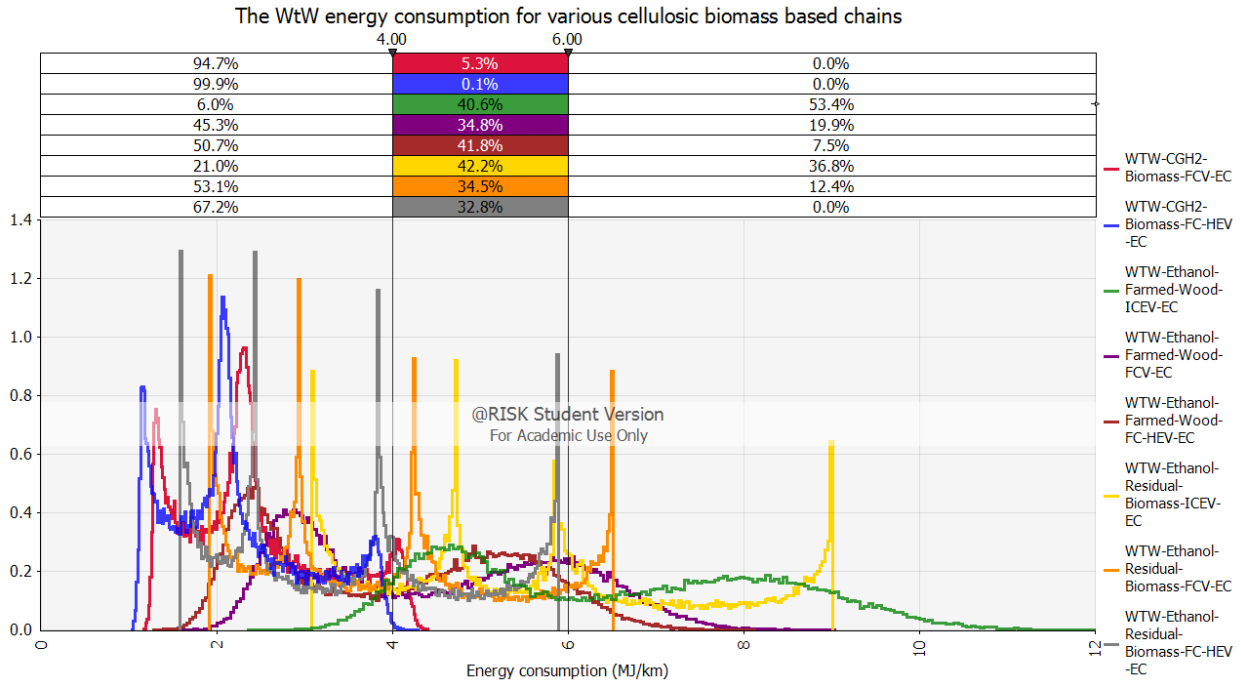


Figure 5.20: The energy consumption distributions of selected cellulosic biomass options

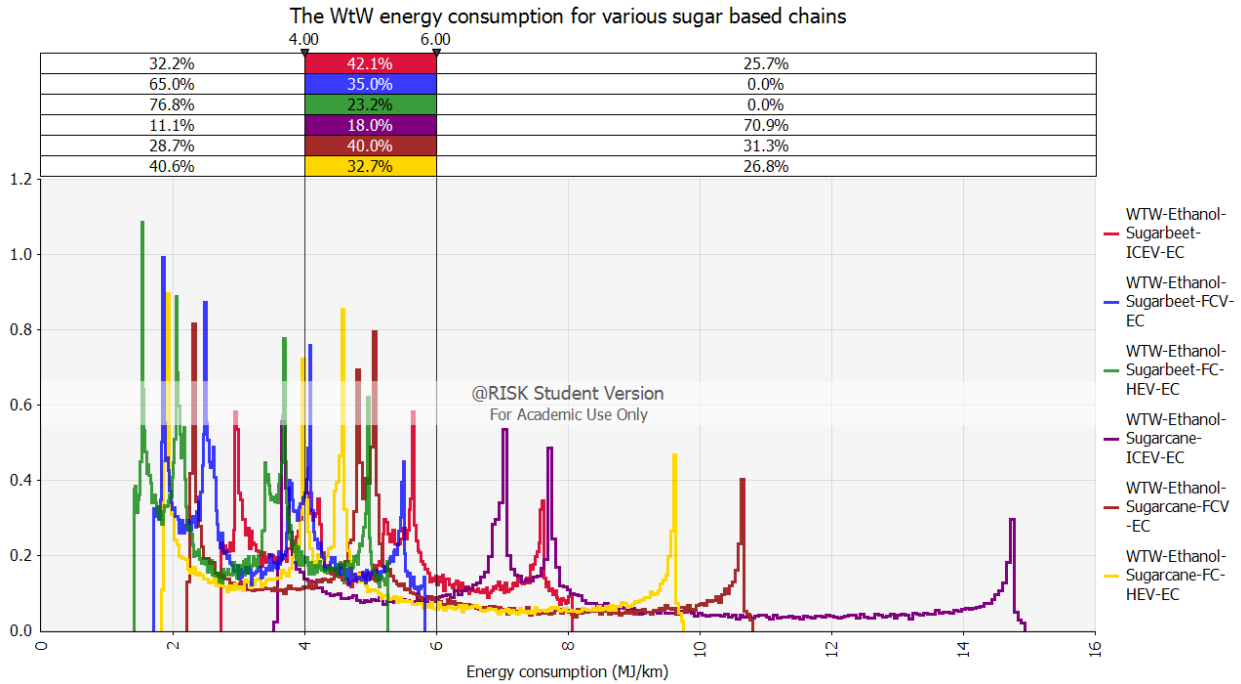


Figure 5.21: The energy consumption distributions of sugar biomass chains

The result of Figure 5.20 reconfirms what was seen earlier in Figure 5.19 concerning the ethanol chains. Cellulosic ethanol chains with ICEV have large population (may exceed 50%) > 6.00 MJ of energy use per kilometre. The second generation bio-vehicles significantly improve the standing of the ethanol chains yet the hydrogen pathways are much superior with 95-100% of the population < 4.00 MJ of energy use per kilometre. The picture is not different with sugar ethanol chains which are even more energy intensive. Again the second generation bio-vehicles significantly improve the standing of the ethanol chains.

However as mentioned earlier, in comparing biomass options that are based on different types of feedstock the energy efficiency has no important implication because biomass resources are non exhaustible. Thus it does not matter whether option A consumes more regenerated energy in comparison with option B which is based on a different type of feedstock, but what really matters is which of the two options consumes more land; where land use efficiency does not necessarily move in tandem with energy use efficiency. Energy use efficiency, therefore, is only important if one compares two or more options that consume the same resource (e.g. sugarcane). Then the same resource should be used in the most efficient manner to encourage decreasing the overall dependency on fossil fuels and benefit from an indirect positive impact on sustainability. Moreover, in such cases the energy efficiency which mainly reflects the efficiency of feedstock use moves in tandem with the efficiency of land use. For instance, in comparing short-rotation forestry wood (farmed wood; e.g. poplar wood) and residual biomass including waste wood for transportation one's attention is turned to the fact that the CGH2 from biomass (including residual and farmed wood) chains are significantly more energy efficient than ethanol from farmed wood or ethanol from residual biomass chains and thus without any doubt the use of wood biomass (farmed or waste) is in favour of the more efficient pathway and that is the hydrogen pathway. More energy efficiency means more kilometres per dry tonne of wood and per hectare in the case of farmed wood. This implies more efficient use of land and/or better sustainability.

5.7.3 GHG emissions of biomass options

As seen in Figure 5.22 below the comparative analysis based on GHG emissions reflects the reason why there has been so much interest in biofuels in the transport sector.

While the biomass-based transport chains are seen as one of the least energy efficient options, on the converse side they are generally seen as one of the most attractive options for GHG emissions savings. Particularly obvious the biomass-based hydrogen chains and wood ethanol chains have a clear potential for significantly reducing GHG emissions relative to the reference chain. In the following analysis use is made of the energy savings distributions to take a closer look on the standing of selected biomass-based options in terms of GHG emissions.

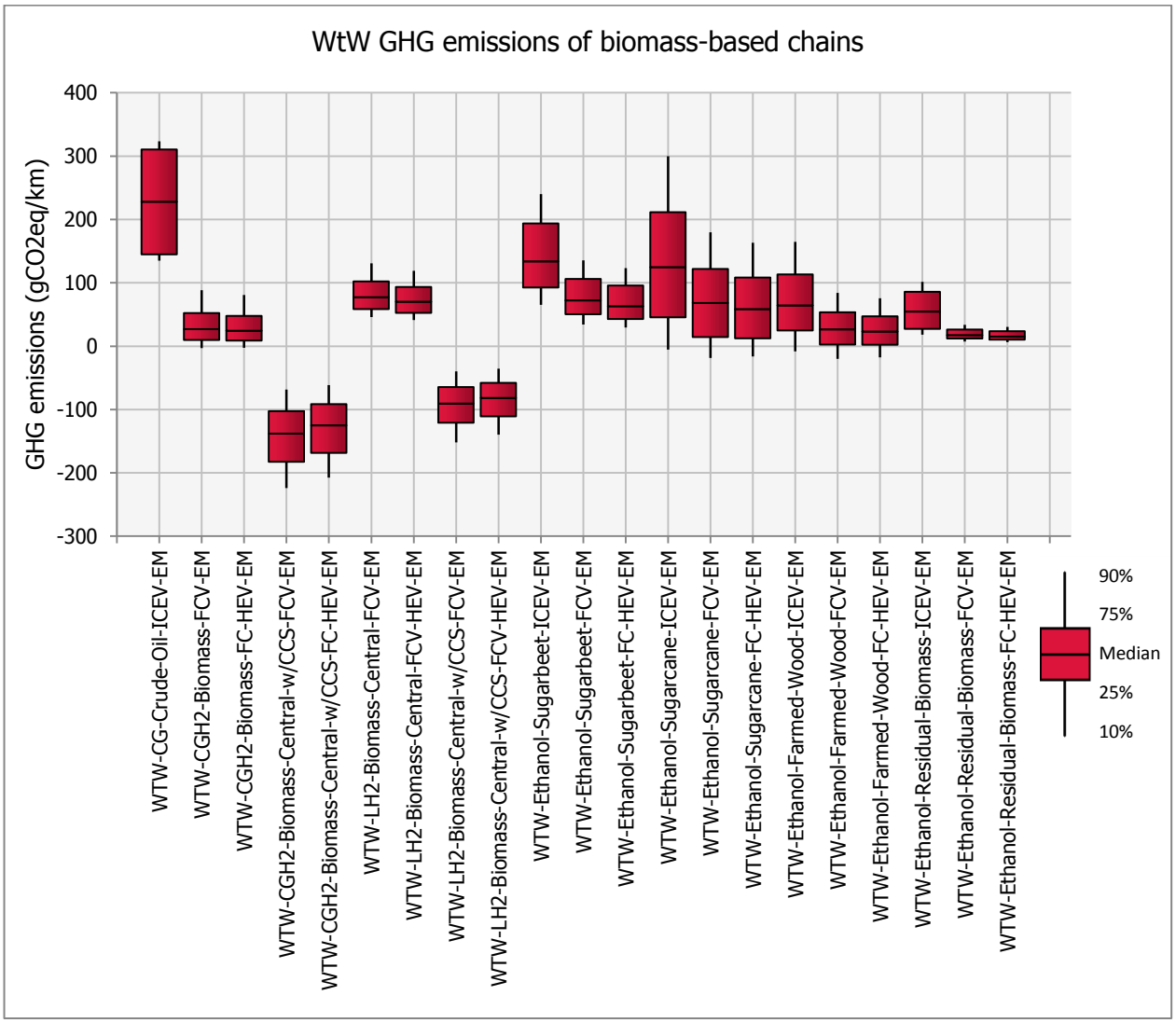


Figure 5.22: The WtW GHG emissions of biomass-based chains

As seen in Figure 5.23 below all the options of cellulosic biomass without exception present large potential of GHG emissions savings with negligible or no population of change in the risk zone and significant population in the defined opportunity zone ($\geq$ 200 gCO_2eq/km of GHG emissions savings). The type of biomass feedstock under consideration in the reference models

for hydrogen production is wood from either waste or short term forestry. With the exception of options with carbon capture and sequestration technology (CCS), the performance of the different options presented above, including CGH2 from wood gasification and ethanol from wood fermentation is similar and cannot be separately profiled. However earlier in this section it was seen that wood gasification has a clear advantage over wood fermentation in terms of energy and land use efficiency.

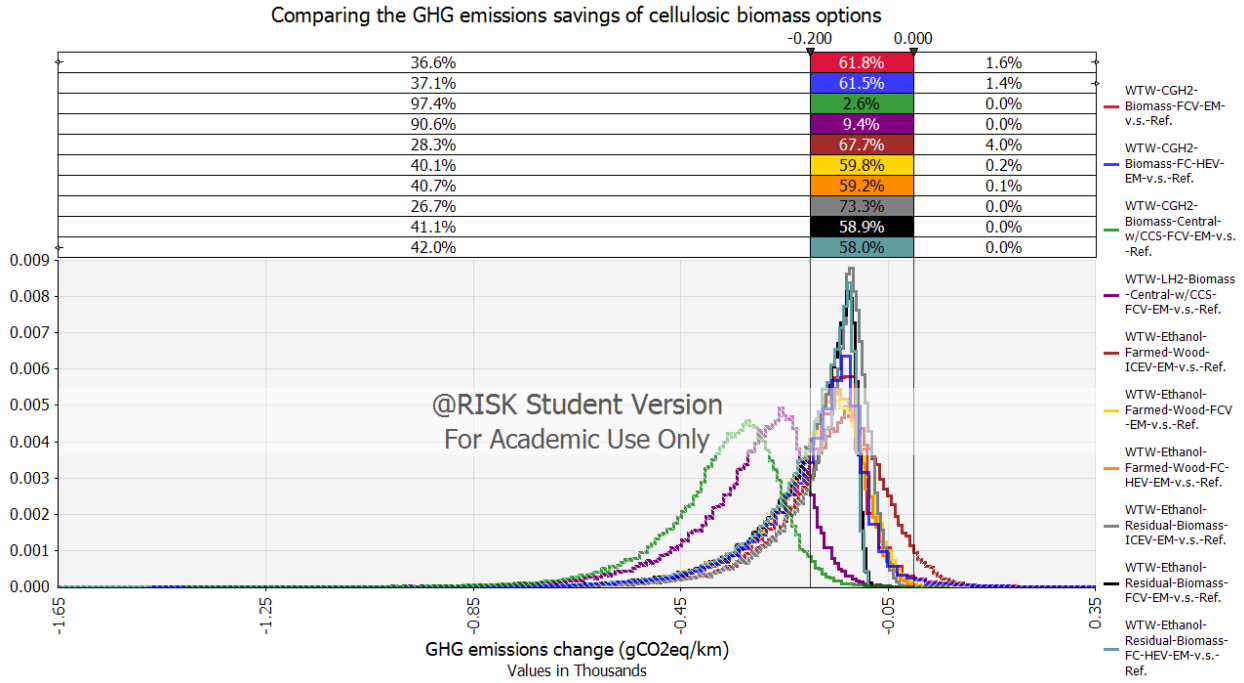


Figure 5.23: The GHG emissions change distributions of selected cellulosic biomass options

Most notable in Figure 5.23 is the effect of carbon sequestration technology on the GHG emissions savings of the hydrogen option. As seen in Figure 5.23 the integration of carbon sequestration to large gasification systems would generate huge GHG emissions savings. The CCS technology adds to the natural carbon sink (soil and plant) another large carbon sink placing the gasification of biomass in a position that no other known option can achieve. Even with the liquefaction of hydrogen for distribution in the form of liquid hydrogen (LH2) 91% of the change population is in the predefined opportunity zone ($\geq$ 200 gCO_2eq per kilometre of GHG emissions savings); this presents an opportunity to avoid the infrastructural requirements of hydrogen distribution. However, as mentioned earlier to complete the analysis there remains questions concerning the technical and economic feasibility of carbon sequestration.

As shown in Figure 5.24 the sugar biomass options have generally less potential of GHG emissions savings as compared to the options of cellulosic biomass. Nevertheless, the sugar biomass options still show very good potential of significant GHG emissions savings with the options that involve second generation bio-vehicles (ethanol fuel processing FCV and FC HEV with integrated fuel processing) presenting no significant risk of GHG emissions debt and with significant population (24% to 32%) of GHG emissions savings in excess of 200 gCO_2eq per kilometre. However, in the case of sugar ethanol chains with ICEVs there is a significant risk of GHG emissions debt that can reach up to 25% with sugarcane ethanol; but this risk does not disqualify the option of sugarcane ethanol with ICEV knowing that there is a large capacity for system optimization and risk elimination.

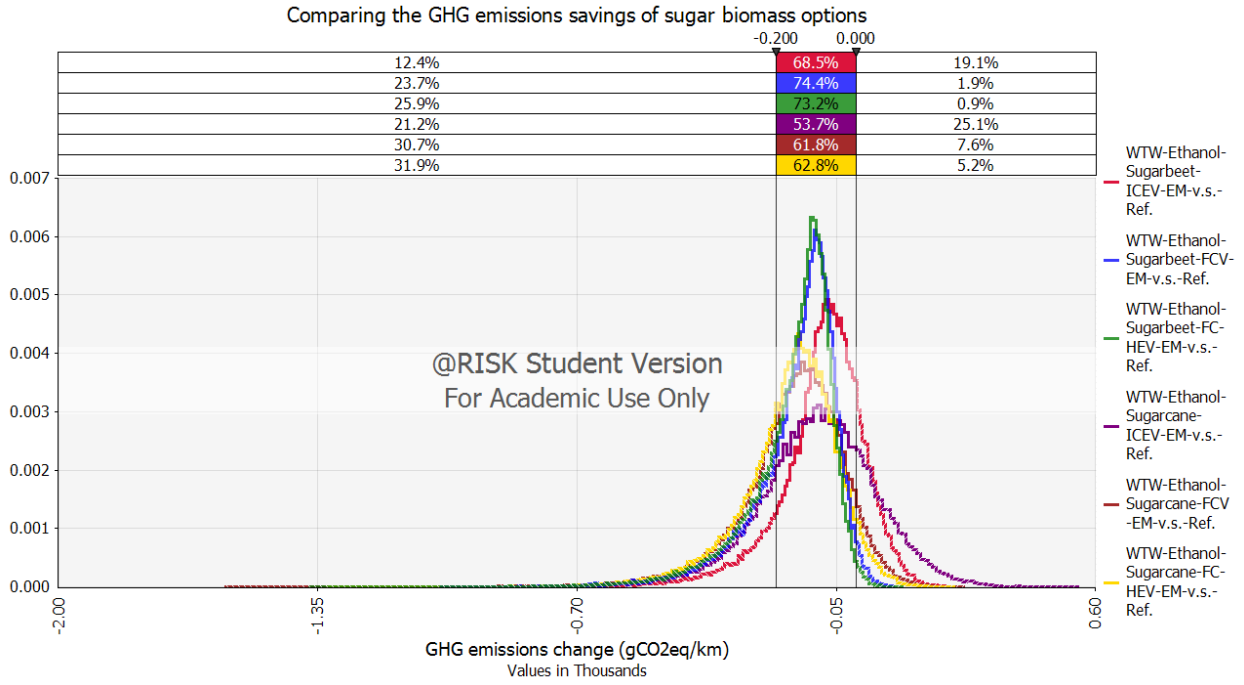


Figure 5.24: The GHG emissions change distributions of selected sugar biomass options

Based on the results of the sensitivity analysis which are summarized in Table 4.8 in Chapter 4, a large proportion of the variability in the GHG emissions of sugar ethanol options is a result of variability in nitrogen fertilizers use, assumption of land use changes (only in the case of sugarcane ethanol as there is large agreement across the reference models on the assumption of land use changes associated with sugarbeet farming) and the carbon balance of the fermentation process under variation in the fermentation yield, process design, allocation method and/or type of displaced system (e.g. coal-fired power plant). In general, farming of degraded or set aside

land to avoid indirect land use changes, low nitrogen fertilizers use and high fermentation carbon balance represent the choices of safe practice in bioethanol production from sugar biomass; these choices reshape the GHG emissions change distributions in Figure 5.24 to eliminate the risk of GHG emissions debt and guarantee small to significant GHG emissions savings depending on whether we are considering ethanol ICEVs or second generation ethanol FCVs.

5.8 Discussion and concluding remarks

5.8.1 General remarks

In this thesis a Standardization Transport Model (STM) was developed for each chain under study by formulating the data in the major databases so that the Well-to-Tank processes covered Feedstock Production, Feedstock Transport, Fuel Production and Fuel Distribution. With the addition of Tank-to-Wheel data, a comprehensive STM was obtained for each chain. For each stage there is a range of values that was characterized by a probability distribution and through the use of Monte Carlo simulation the distribution was sampled and overall values for the total energy consumption, in MJ/km, and total GHG emissions in grams of carbon dioxide equivalent per kilometre (gCO_2eq/km) were generated. The output is represented by distributions as shown earlier. By statistical means these distributions were compared to assess the risk of debt as well as the likelihood of major savings. The implications of the specific outputs are considered shortly.

Firstly two general points are made. Firstly as shown in Figure 5.1, the introduction of hybrid technology into a chain has the greatest effect in terms of both energy consumption and GHG emissions for the conventional gasoline engine and the CNG engine chains. There is a lesser benefit for other chains. Secondly as expected, the inclusion of CCS technology is seen to largely curb carbon emissions for hydrogen FCVs and BEVs fuelled by NG or coal electricity. However, the analysis is incomplete without the technical and economic feasibility of CCS being considered.

5.8.2 Optimising the use of Natural Gas

It is clear that the non-hybrid CNG ICEV chain is neither a secure option with respect to either energy or GHG emissions. Interestingly NG-based electricity fuelled BEVs are more or less on a par with NG-based hydrogen FCVs and the integration of hybrid technology to CNG ICEV

changes the positioning of CNG as an alternative fuel; it is placed in a similar positions as hydrogen. It is only by assuming the highest efficiency for steam reforming of methane (SMR) for hydrogen production, the lowest energy consumption and GHG emissions for hydrogen compression for hydrogen distribution, and/or the highest efficiency for CCGT power plant for NG-based electricity production that one can rank the hybrid CNG chain lower than hydrogen FCVs (based on NG resource) and NG-electricity BEVs.

5.8.3 Comparison of hydrogen FCVs and BEVs

Generally the use of NG in the transport sector does not guarantee considerable energy and GHG emissions savings. Nevertheless, with the appropriate choice of processes for the optimization of the use of NG, the assumptions change and one can guarantee significant energy and GHG savings. As noted earlier in the previous section NG-based electricity fuelled BEVs are more or less on a par with NG-based hydrogen FCVs. On the other hand, renewables are generally far superior to NG for use in the transport sector as large GHG emissions savings ($\geq$ 100 gCO_2eq/km) are almost guaranteed by all renewable options. But when the question: Hydrogen economy: myth or fact? is raised it has to be noted that BEVs are superior to hydrogen FCVs. Renewables driven BEVs are in a significantly better position compared to corresponding hydrogen FCVs in terms of energy efficiency. This implies much better sustainability. However, as seen in Figure 5.8 in terms of GHG emissions savings there is not much difference between the renewable based BEVs and the equivalent hydrogen FCVs. The picture does not change with respect to nuclear power; nuclear electricity driven BEVs are far superior to their hydrogen FCV equivalents. Indeed the conclusion for hydrogen FCV ultimately fuelled by nuclear electricity is strongly discouraging; this chain is a non-starter when looking at the impact on sustainability in terms of energy.

So, in general, is there a place for hydrogen FCV? The answer without an account of the potential role of biomass in transportation may well be “no”. On an energy basis BEVs are generally superior with the only downside being their range and recharging rates. If the latter can be accelerated and the former improved there would seem to be but a minor role for hydrogen FCVs.

The coal-electricity driven BEV option guarantees, with respect to the reference chain, an energy credit and uses a less valuable fossil fuel. However without CCS technology it presents very high

probability of increasing GHG emissions. If BEVs were to become widespread the source of their electricity becomes a very important consideration.

5.8.4 The potential role of biofuels

The options for bio-ethanol present very high profiles of energy use and are generally the least energy efficient alternatives. Nevertheless, in the case of biomass use the criteria of choice among options of different types of biomass are listed with decreasing priority as follows: (i) land use and competition with food/feed markets, (ii) GHG emissions and (iii) energy efficiency (which has no implications on sustainability unless one is comparing different options of the same type of biomass). Among the options that are based on cultivated biomass the sugar ethanol options are the best in terms of land use with sugarcane having the advantage of being economic and available for short-term penetration. The development of second generation ethanol vehicles largely improves the energy consumption of sugar ethanol options and results in a decrease of dependency on exhaustible resources and an increase in land use efficiency.

On the other hand, the use of cellulosic feedstock in passenger cars transportation is definitely in favour of the hydrogen pathways which are significantly more energy efficient as compared to the ethanol pathways. This implies much better sustainability and much more efficient use of land in the case of cultivated wood. Nevertheless, the waste wood feedstock is particularly a very promising second generation resource with no associated land use change and no competition with food/feed markets.

Ultimately the reason behind so much interest in biofuels is their high potential for GHG emissions savings. In fact there is no notable risk of GHG emissions debt associated with cellulosic biomass options which on the contrary have a high potential for large GHG emissions savings. Also sugar ethanol options with second generation ethanol vehicles present very small to insignificant risk of debt and good potential for large GHG emissions savings. The safe implementation of sugar ethanol by farming on degraded or set aside land, low nitrogen fertilizers use and low carbon footprint for fermentation (high carbon balance) guarantees significant GHG emissions savings. In the case of residual biomass based ethanol-fuelled FCVs the variance of GHG emissions is very small (Figure 5.22) and thus has almost no impact on the change distribution.

The effect of CCS technology on the standing of bio-hydrogen is most notable. The integration of CCS places bio-hydrogen in a position that no other fuel alternative is known to achieve. Even with the liquefaction of hydrogen to avoid the infrastructural requirements for hydrogen distribution the majority of the population has a very large GHG emissions savings ($\geq$ 200 gCO_2eq/km). Nevertheless, the production of biofuels from cultivated biomass follows a bell-shaped curve and cannot be sustained on the long run. Only the production of bio-hydrogen from waste wood (e.g. forest residue) is independent of land use and presents a second generation option that can be sustained on the long run for significant to large GHG emissions savings without CCS technology. Thus hydrogen FCVs may be important in the biofuels market for the incorporation of waste wood and in the case of feasible CCS contribute significantly to GHG emissions savings.

5.8.5 Final remarks

All major WtW models were combined so as to generate an output which has statistically sound measures, including the uncertainty that arises from the variability of the modelling elements in the major models. Through this aggregation of information, the gap between specific WtW analyses and policy making was bridged. The results generated include a measurement of uncertainty and so possess the robustness required for strategy-making. The results will provide informed answers to many energy policy questions that have been strongly debated including the viability of the hydrogen economy.

Hydrogen has been considered by many to be a promising carrier, in the transport sector, for the use of different types of resources including NG, biomass and non-biomass renewables (e.g. hydro, wind, etc). However hydrogen FCVs perform similarly or worse than BEVs. In the case of nuclear resources, hydrogen FCVs are a complete non-starter on an energy basis; also in the case of non-biomass renewables the electric pathway is significantly more energy efficient than the hydrogen pathways implying less dependency on exhaustible resources such as fossil fuels in the transport sector. In fact the role of hydrogen is found to be limited to the incorporation of cellulosic biomass such as waste wood in passenger cars transportation. Thus one can envisage a minor role for hydrogen in the transport sector and the realization of the so-called hydrogen economy is a questionable objective.

Reliance upon BEVs will be detrimental if the electricity is coal based without the implementation of CCS technology. However with electricity from renewables or nuclear or even NG fuelled high efficiency CCGT power plants, BEVs guarantee significant reductions in GHG emissions with the guaranteed reductions in GHG emissions for nuclear and renewables fuelled BEVs being large (nearly 100 gCO_2eq/km).

From a societal perspective energy consumption per km and GHG emissions per km are the two most relevant metrics. The individual driver will however be concerned with the distance that can be driven before charging and the time for charging. It can be anticipated that successful resolution of these two issues will place BEVs above hydrogen FCVs in the same way that railways were found to be superior to canals. Nevertheless, hydrogen is not the mature short term option; in fact hydrogen technologies from production to use are still under development and considerable time and effort is required before they penetrate the market.

On the other hand, sugar based bioethanol promises significant to large GHG emissions reduction while the indirect land use change is avoided. Actually the implementation of biofuels stands on avoiding competition with food demand and indirect land use change. The real limitation of biofuels, however, is land use which is believed to enforce a bell-shaped curve on the production of biofuels from cultivated biomass.

6 New Boundary for Transport Systems Analysis

6.1 Introduction

As mentioned earlier the past decade has witnessed an accelerated use of the WtW approach to assess the sustainability of prospective transport systems for medium to long term futures. However, it is puzzling to notice that all the major WtW studies on this subject such as those completed by General Motors Corporation (GM) in collaboration with Argonne National Laboratory (GM *et al.*, 2001), the European Union (GM *et al.*, 2002b), and others (Wang, 1999; Weiss *et al.*, 2000; Edwards *et al.*, 2007) restrict the boundary of the analysis to processes associated with transport and bypass the synergies between the transport sector and other major sectors of energy resource use. A similar situation existed with regard to the Greenhouse Gases (GHG) footprint of biofuels. However in a notable paper Searchinger *et al.* (2008) examined the synergies between the transport sector and food markets and introduced the concept of the indirect land use change (iLUC). This sparked controversy over their counter-claim regarding greenhouse gas (GHG) emissions benefits available through a switch to biomass. A similar change is required for the transport-energy nexus but so far transport analysts have not redrawn the boundary for the analysis of prospective transport fuels.

The concept of indirect land use change is based on resource sharing and for biofuels production the primary resource is land. In simple terms, the change of land use to a biomass plantation will exert pressure on the food supply and induce land use changes somewhere else to stabilize the food markets and overall this can have large negative implications on the GHG footprint of biofuels systems. The question that arises here is of whether land is the only point of intersection between the prospective transport systems and other major systems of energy resource consumption?

Besides the transport sector, the power sector is another major sector of energy resource consumption and careful consideration of any synergies between the two sectors is essential for the completeness of the analysis. The traditional transport system based on crude oil does not intersect competitively with the power systems because the gasoline fraction of crude oil is

almost exclusively used in the transport sector.[15] However, some of the prospective transport fuels such as hydrogen and electricity are based on NG, renewables and uranium and these do intersect with the power systems by sharing of primary energy resources. This consequently implies synergistic behaviour between the power and transport sectors that is not seen through the traditional boundary for the analysis of transport fuels.

It is argued below that there is a correct sequence for the use of alternative resources and that is shaped by the synergistic behaviour between the transport and power sectors. In this chapter a new boundary is drawn for the analysis of prospective transport fuels, relevant relationships are defined and various scenarios examined. To do this we draw on the results of the LCA of prospective transport systems, in terms of energy consumption and GHG emissions, obtained from our standardization of major Well-to-Wheel (WtW) models.

6.2 Synergies between power and transport

First, a clear distinction between the conventional uses and the alternative uses of energy resources is made. The resources considered for prospective transport systems (NG, renewables and uranium) are currently used in the power sector as an increasing substitute for the conventional resource of coal and primarily do not relate to the transport sector. The use of alternatives in the transport sector will be a diversion from their original use in the power sector. This is in the same way that crops such as wheat and corn, which were originally used only as food products, are now in part diverted into the transport sector. Secondly it is necessary that the conventional system in each major sector of energy resource use is defined as measures will be made relative to a reference system and that is the conventional system which by sequence is the least green system in place. The conventional system for passenger car transport is based on crude oil mainly through gasoline and there has been very little substitution of this system in the past. On the other hand, the conventional system for power generation was based on cheap, abundant coal but there has been some significant substitution of this system. For instance, today

[15] The heavy fraction of crude oil is used as a fuel for power stations when it is not cracked or hydro-treated to produce lighter products. However the sending of fuel oil to a power station can be viewed as the economic disposal of a low value by-product. The fractions entering the transport sector are not used in the power sector and therefore the synergistic links have been mainly non-competitive.

non-coal resources make up 72% of the UK power fuel mix (DECC, 2010b, p.120). Globally coal remains the major resource in the power fuel mix.

The alternatives such as NG, nuclear and renewables are conventionally used in the power sector to (i) augment the conventional power system in meeting increased power demand and (ii) substitute the conventional power system at constant power demand in order to clean up the power sector and reducing the emissions of GHG and other environmentally harmful gases such as NO_x. When a new market for the alternatives emerges and their use is diversified to include the transport sector tensions will be created between the power and transport markets. This will induce what we call the indirect resource use change (iRUC) where as a result of the tensions between the markets some of the alternatives already used in the power sector are dragged to the transport sector and a power gap is left to be compensated by the business-as-usual which is the conventional power system. The reinstatement of the original level of energy supply in the power sector will induce some change in resources used, which is the iRUC. This will be shown below to increase global GHG emissions. In particular cases this can be very large depending on the type of conventional power system in place and the size of the tensions generated between the power and transport sectors. Nevertheless, in an alternative scenario of synergy between the power and transport sectors where the use of the alternative resources is not diversified but fed only into the power sector any iRUC can be avoided and "double use" made of the alternative resources. This is firstly in their conventional use to displace the conventional power resources (with improvements there) and secondly in the use of the displaced resources (i.e. resulting excess power capacity) to supply the transport sector to make further reductions in the global emissions of GHG in that sector through displacement of gasoline. The end result is maximizing the global reduction of GHG emissions and the maintenance of upstream energy security.

6.3 Scenarios

This study is focused on scenarios in which either competition for new resources between the power and transport markets is envisaged or the use of alternative resources is preferentially given to the power sector. In this chapter scenarios of synergies between the two major sectors of fuel consumption, i.e. the power and transport sectors, will be illustrated by using paired scenarios. For the use of alternative resources as described in the scenarios below estimates of the global changes in GHG emissions will be made.

Scenario 1:

NG is used in the transport sector to displace an equivalent amount of oil[16] while coal is used as the conventional fuel in the power sector. In this scenario it is assumed that the diversion of NG use to the transport sector will induce iRUC on a ratio[17] of 1:1 because the NG supply is already very stringent without the interference of the transport sector. In other words the assumption is that every unit of NG going into the transport sector is taken from the power sector. The calculations are made for 100 MJ of NG resources used in the transport sector. In fact, in the UK the supply of NG is sensitive to changes in price and other factors. The share of NG in the power fuel mix has stabilised at around 46%; the most recent statistic for NG share in the power fuel mix is 45% in 2009 down 1% from 2008 (DECC, 2010b, p.120). The introduction of new technology is assumed to include CCS.

Scenario 2:

The power sector is not disturbed and an amount of new coal resources, equal to the amount used in scenario 1, to compensate for the power gap created by market tensions, is directly used (with CCS technology) to produce electricity for the transport sector. This scenario, like scenario 1, relates to the short-term future. In scenario 2 there is no pressure on the power supply because coal is used in the transport sector as it is phased out from use in the power sector.

Scenario 3:

This scenario and the next are more medium term than the first two. The nuclear power is used in the transport sector via conversion to hydrogen or electricity while some fossil fuels including coal are still used in the power sector. Thus, some new nuclear power which is originally viewed as an alternative in the power sector is diverted for use in the transport sector. In this scenario it is assumed that nuclear power supply is not very stringent as nuclear power plants are commissioned at a high level and so with a planned concurrent increase in the use of nuclear

[16] The equivalent amount of crude oil use in the transport sector is the amount of crude oil required to generate the same work that is generated by the amount of alternative resource diverted to the transport sector.
[17] Ratio of for example 1:5 means that for every 5 MJ of resource used in the transport sector, 1 MJ is derived from the power sector.

power in the power sector the iRUC is assumed to be incurred on a ratio of 1:5 and the calculations are made for 100 MJ of uranium resources in the transport sector.

Scenario 4:

The transport sector is supplied with coal which has been displaced from the power sector by uranium. The calculations are based on an amount that equals the new uranium resources used directly for transport in scenario 3. For the production of electricity from the displaced coal, CCS technology is employed. In this scenario there is no pressure on the power supply because coal is used in the transport sector as it is phased out from use in the power sector, i.e. power sector remains independent of the transport sector.

Scenario 5:

This scenario and the next are longer term scenarios in which it is assumed that coal has already been phased out of the power sector. In scenario 5, some new renewable power resources are directly assigned to the transport sector with NG considered to be the conventional fuel in the power sector. In this scenario it is assumed that the supply of renewable power supply is not stringent as renewable power is envisaged as being widely implemented following a technological breakthrough. The iRUC is assumed to be incurred only on a ratio of 1:10 and that as the NG supply is very stringent, the power gap will be closed through the use of more nuclear power. The calculations are made for 100 MJ of renewable resources used in the transport sector.

Scenario 6:

The transport sector is supplied with NG which has been displaced in the power sector by an amount of renewables[18] equal to the amount of new renewables used directly in transport in scenario 5 and CCS technology is used to support the electricity produced for the transport sector. In this scenario there is no pressure on the power supply because NG is used in the transport sector as it is phased out from use in the power sector. The transport sector is also

[18] Renewables in the current analysis refer to hydro, wind, solar and geothermal but does not include biomass of any type. Non-biomass renewables are harnessed in the form of electricity, i.e., the energy account of non-biomass renewables starts after conversion into electricity.

supplied with uranium equal to the amount used in scenario 5 to offset the power gap created by the iRUC.

6.4 Methods

The life cycle data used in the current analysis is drawn from the results of the STM which formed the main subject of the previous chapters. Nevertheless, the type of standard results used in the current analysis to estimate the global reduction in GHG emissions for the various scenarios is different from the type of standard results produced for analysis confined to the transport sector. The analyses in the current chapter involve variability in both (i) the *type* of energy resource used and (ii) the *sectorial distribution* of energy resources between the transport and power sectors. Thus the conventional units of the WtW results such as grams of carbon dioxide equivalent per kilometre (gCO_2eq/km) in the transport sector and gCO_2eq/kWh in the power sector are not suitable for weighting the measured quantity (e.g. GHG emissions) across different sectors of energy resource use; like-with-like is required.

However, as emphasized earlier in Chapter 2 the STM can also be used to generate WtW results such as the GHG emissions expressed in the forms of gCO_2eq per 1 MJ of work done (can be a drive, or any type of work). This form of results is normalized to enable comparison across different sectors of energy resource use. In fact the data for the life cycle GHG emissions and primary resource consumption of the different power and transport systems used in the current analyses is expressed in the form of gCO_2eq/MJ_W and MJ_R/MJ_W, respectively, where MJ_W refers to 1 MJ of work done and MJ_R refers to 1 MJ of resource (e.g. coal) and is directly drawn from the STM results as presented in Figure 6.1 and Figure 6.2 below. The assumption made is that all the energy used on a life cycle basis originally stems from the primary energy resource (R) upstream of the chain. The following example illustrates how the global reduction in GHG emissions is calculated for different scenarios. Scenario 4 is taken as an example. First, 100 MJ of uranium displaces an equivalent amount of coal in the power sector (amount of coal that produces the same work done). The uranium power system is designated in this example as $S1$. The work done from the use of 100 MJ of uranium in power is equal to $100/E_{S1}$ MJ_W where E_{S1} is the WtW energy consumption of system $S1$ per 1 MJ_W. (Given that the STM produce variable output the median values are used for quantitative analysis.) Then the GHG emissions from the use of 100 MJ of uranium in power is calculated as $100(EM_{S1}/E_{S1})$ gCO_2eq where

EM_{S1} is the WtW GHG emissions of system $S1$ per 1 MJ_W. On the other hand, the conventional coal power system is designated in this example as $S2$. The GHG emissions from the use of an equivalent amount of coal is calculated as $100(EM_{S2}/E_{S1})$ gCO_2eq where EM_{S2} is the WtW GHG emissions of system $S2$ per 1 MJ_W. Thus, the global change in GHG emissions from the displacement of coal is calculated as $100(EM_{S1} - EM_{S2})/E_{S1}$ of grams of CO_2 equivalent.

Second, the amount of coal displaced in the power sector which is equal to $100(E_{S2}/E_{S1})$ MJ_{coal} is used in the transport sector through BEV and with CCS technology implemented to the coal power plant. This transport system is designated in this example as $S3$. The global change in GHG emissions from $100(E_{S2}/E_{S1})$ MJ_{coal} displacing an equivalent amount of oil in the transport sector is calculated like in the first change above as $100(E_{S2}/E_{S1})\,(EM_{S3} - EM_{S4})/E_{S3}$ of grams of CO_2 equivalent where $S4$ designates the conventional transport system.

Finally, the net global change in GHG emissions is the sum of the changes in the transport and power sectors and that is $100(EM_{S1} - EM_{S2})/E_{S1} + 100(E_{S2}/E_{S1})\,(EM_{S3} - EM_{S4})/E_{S3}$ of grams of CO_2 equivalent.

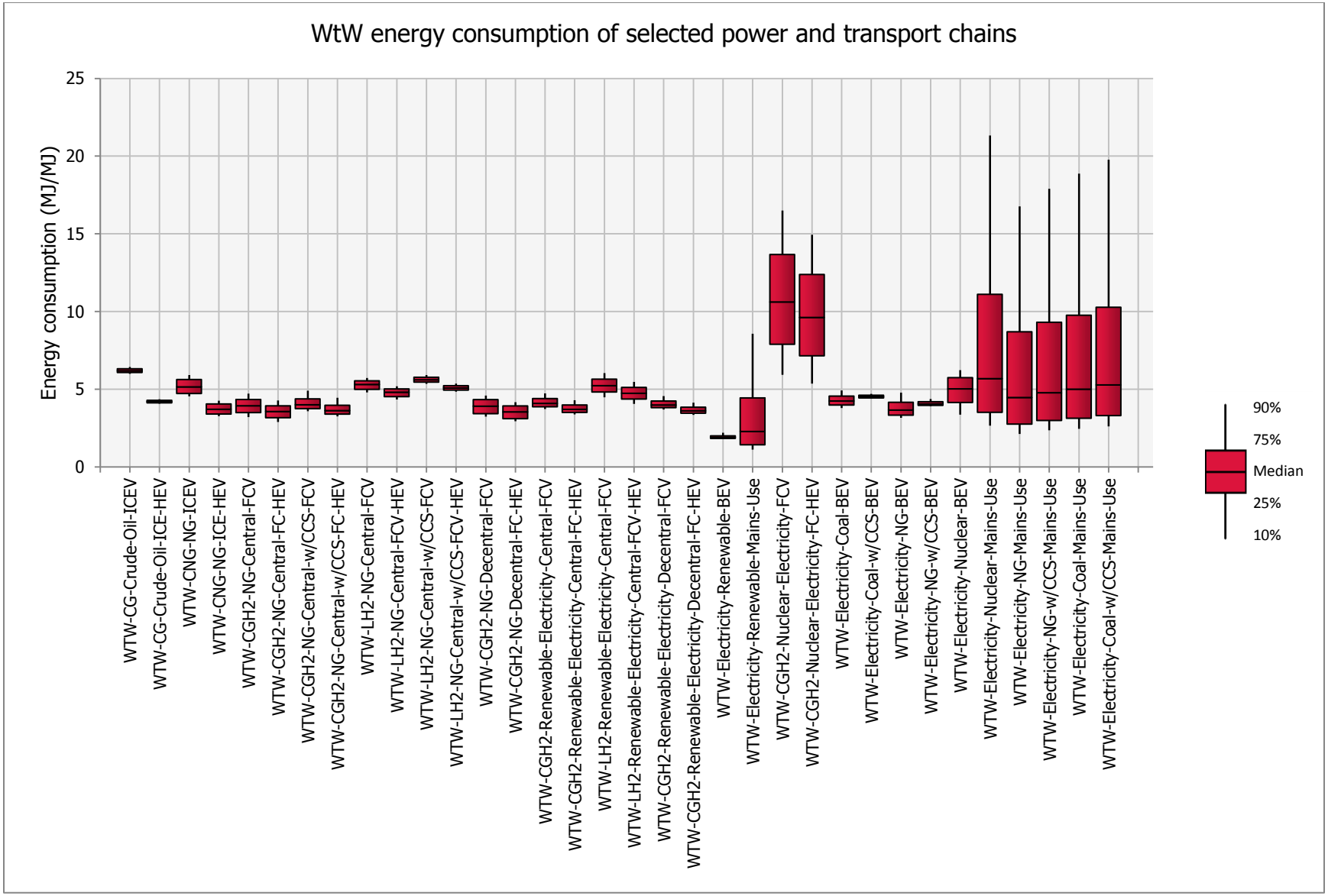


Figure 6.1: Energy consumption in MJ/MJ_W for relevant WtW power and transport chains

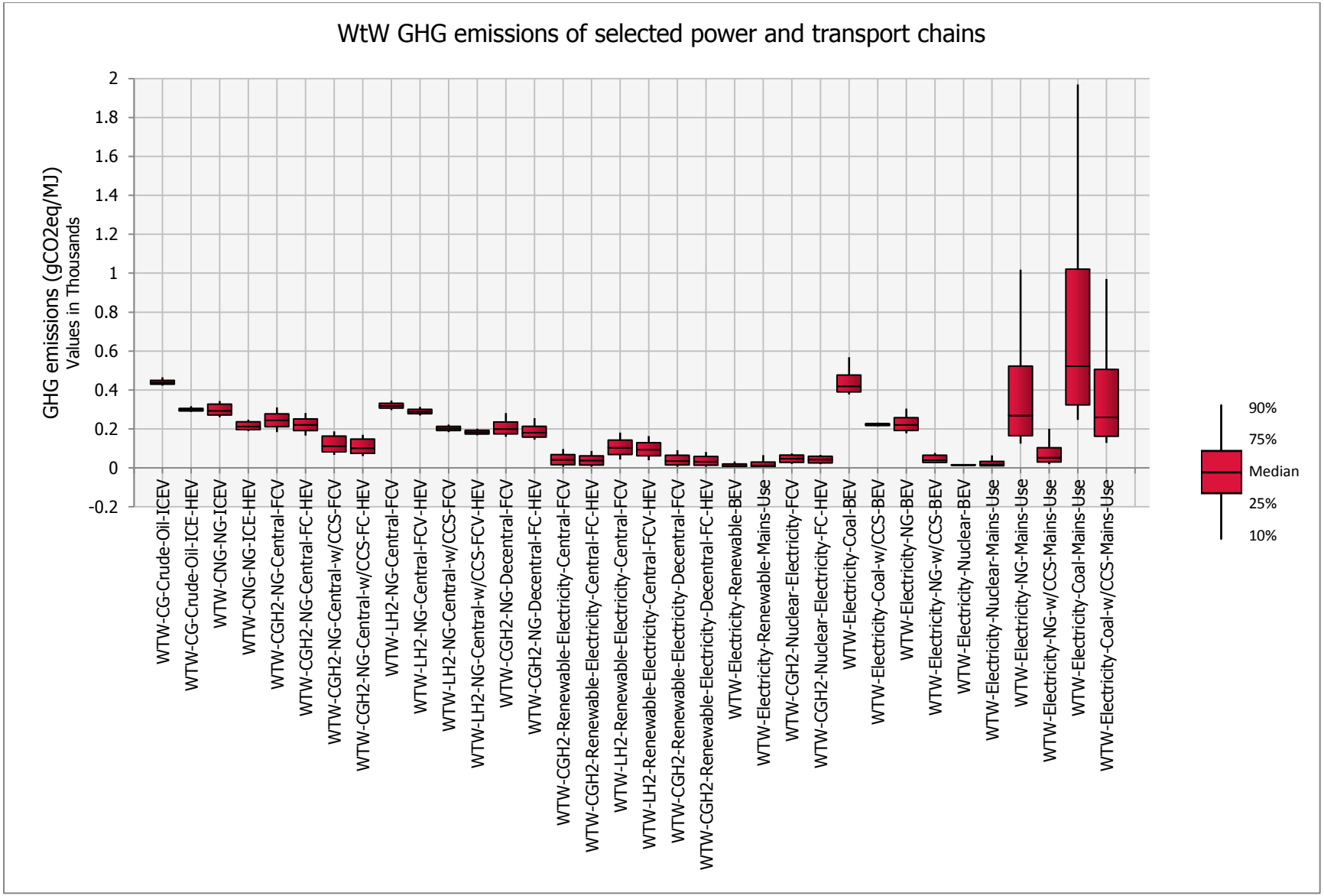
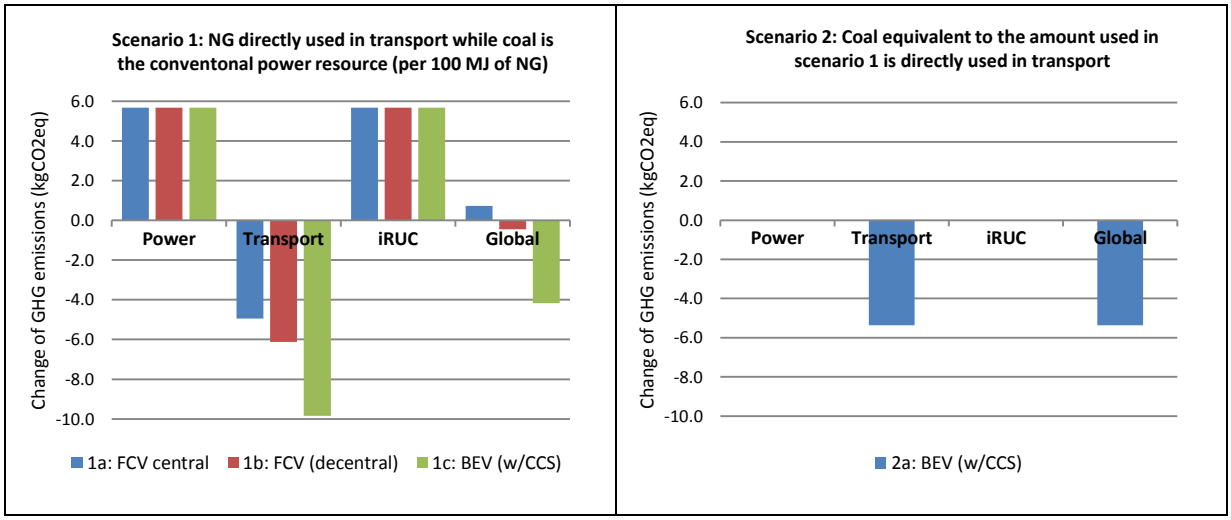


Figure 6.2: GHG emissions in gCO_2eq/MJ_W for relevant power and transport chains

6.5 Results and discussion

The charts below depict the changes of GHG emissions associated with the synergistic behaviour between the transport and power sectors for the scenarios described in Section 6.3. The calculations cover FCV, central and decentral, and BEV (w/CCS where applicable). The global changes in GHG emissions take into account the iRUC effect where applicable. Until now studies on the ecological GHG balance of prospective transport systems have not accounted for the GHG emissions associated with the iRUC which as seen in Figure 6.3 can significantly affect the global reduction in GHG emissions associated with the implementation of prospective transport systems depending on the conventional power system in place and how stringent is the supply of the resources under consideration. The outcome for scenario 1 shows that whilst one can anticipate reductions in GHG emissions by a switch from gasoline to either hydrogen or BEV (w/CCS at the power station) the changes can be negligible if the power lost from the power sector is replaced by power from conventional coal fired stations. The iRUC effect is equal to the negative effect at the power station.



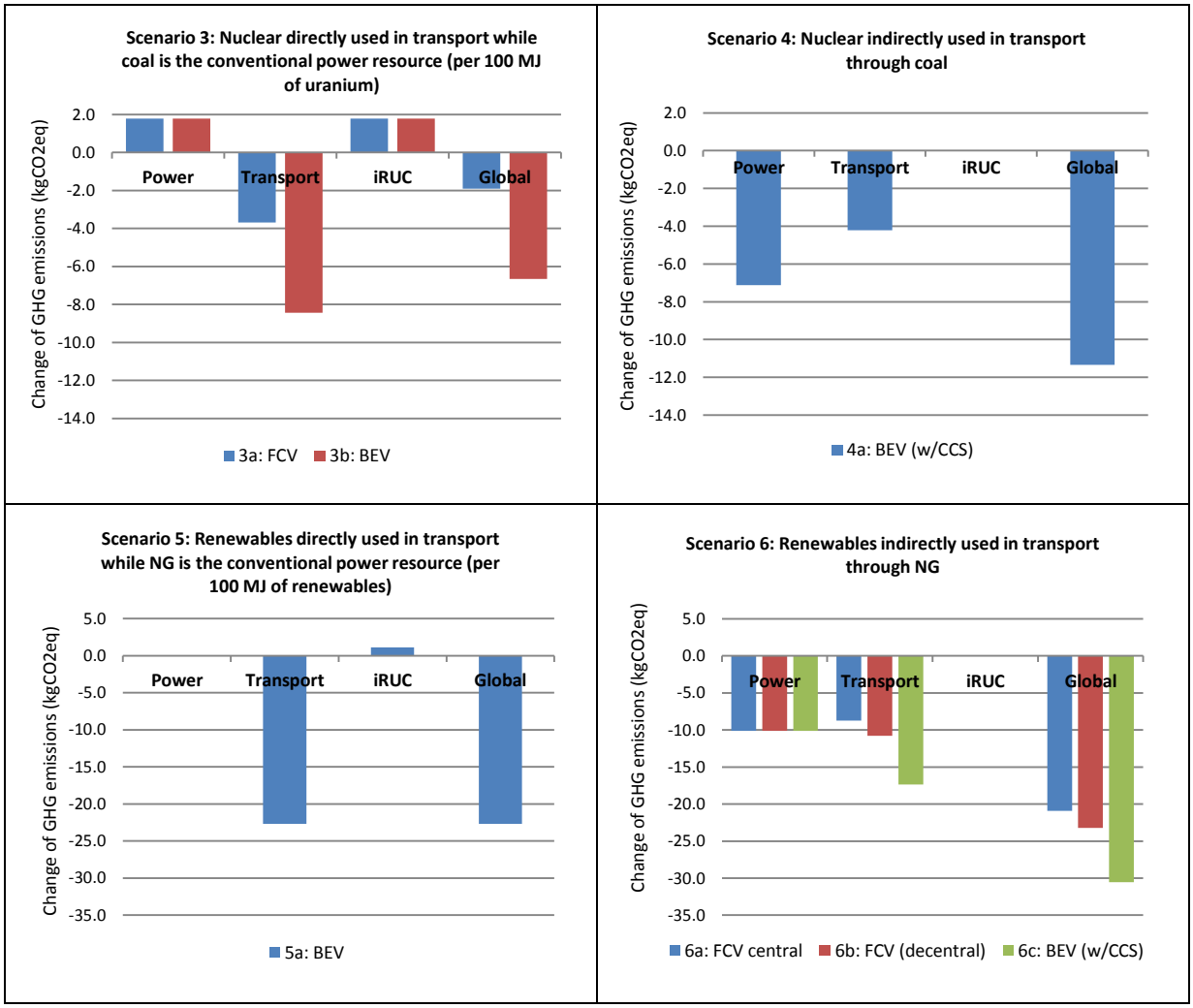


Figure 6.3: The changes of GHG emissions from the use of alternatives under different scenarios

The scenarios for the use of alternatives either represent a "transport push" or a "transport pull" depending on the sequence of events. When alternatives are used directly in the transport system we generate a "transport push" on the power sector which exerts pressure on the power supply and induces iRUC whereby the conventional power system must compensate for the resource removed from it because of market tensions. Although the iRUC may be offset by using another conventional fuel in the power sector, there is an overall, generally negative, effect on GHG emissions. As seen in scenario 1 in Figure 6.3 above, the use of NG in the transport sector given the assumption that the supply of NG is very stringent, induces large iRUC emissions as the NG used in the transport sector is compensated by cheap, abundant coal in the power sector. For the best NG-based transport system, the iRUC reduces the global reduction in GHG emissions from 9.85 to 4.17 $kgCO_2eq$. However if the amount of coal equivalent to the NG compensated in scenario 1 is used directly in the transport sector (scenario 2), the global reduction will be about

1.2 kg of CO_2 equivalent better at 5.4 $kgCO_2eq$. The latter scenario is shown in Figure 6.3 as scenario 2. Thus it is seen that the iRUC can be very significant and should not be neglected in the analysis of prospective transport systems. The traditional boundary for the analysis of transport systems disguises the actual global change in GHG emissions.

The avoidance of iRUC is not the only factor that is important when planning the implementation of alternatives. It is very important that we maximize the benefits from the use of available resources. There are two scenarios assumed for the use of new nuclear capacity and these are presented by scenarios 3 and 4 in Figure 6.3. The former scenario represents a "transport push" where the use of the nuclear resources is diverted to the transport sector bypassing the power sector. The drawbacks of such a scenario are firstly that the market tensions will induce iRUC, though in the case of scenario 3 it is not as large as in the case of scenario 1 because nuclear power is assumed (in this scenario) to be widely implemented on a large scale. Secondly energy security is reduced because if the conventional power resources cannot be increased to compensate for the gap created by market tensions society would face a power crunch. Thirdly and most importantly, the bypassing of the power sector will take away the opportunity of making maximum use of the nuclear resources. When the nuclear power displaces the conventional system in the power sector creating large GHG emissions savings in that sector, whilst concurrently use is made of the displaced coal capacity to produce electricity for the transport sector, one makes savings in two sectors simultaneously and thus maximizes the global reduction in GHG emissions. This is the case in scenario 4 which represents a "transport pull" where the nuclear resources create large GHG emissions savings in the power sector and an opportunity for further savings in the transport sector. The transport sector pulls the "freed" conventional resources from the power sector and makes further GHG emissions reductions.

In a transport pull scenario one avoids iRUC and no pressure is exerted on the power supply because the power market is not in competition with the transport market. For scenarios 3 and 4, the end results are much larger global reduction in GHG emissions (the reduction increases from 6.66 to 11.33 $kgCO_2eq$ assuming the introduction of CCS in scenario 4) and better energy security.

The comparison of scenarios 5 and 6 for the use of renewable resources reconfirms what was observed earlier and that is that the "transport pull" scenario results in better upstream energy

security and much larger reduction in global GHG emissions as compared to the "transport push" scenario (the global reduction in GHG emissions increases from 22.68 to 30.53 $kgCO_2eq$).

6.6 Concluding remarks

In the planning of passenger car transport it is important that the focus be widened to assess global benefits. The resources to produce hydrogen and electricity for transport will potentially have effects on the power sector through the displacement of resources. As part of a study for DTI on a strategic framework for hydrogen energy in the UK a range of people involved in directing and implementing UK energy policy were interviewed about long term priorities. According to the interviewees the main goals beyond 2020 are: (i) competitive CO_2 reductions and (ii) improved upstream energy security (E4tech *et al.*, 2004). The observations made in this chapter deliver a very important message in this respect and that is the use of alternative resources in line with these goals should be done in a correct sequence taking into account the synergistic behaviour between the power and transport sectors to maximize both the global reduction in GHG emissions and upstream energy security.

The general rule in frame working the future of transport systems for the goals defined above is: *Never bypass the conventional power systems*. The alternatives such as NG, nuclear and renewables should not be diverted from use as alternatives in the power sector and should only be used in the transport sector through a "transport pull" scenario. When this is done one (a) avoids iRUC and makes use of the conventional power resources displaced from the power sector to maximize the global reduction in GHG emissions, and (b) one isolates the power market to maintain the upstream energy security.

Looking to the future the optimal sequence is:

1. While coal is still present in the power mix and that is the case today[19] any new alternative power capacity such as nuclear power capacity should be used to displace coal

[19] Department of Energy and Climate Change (DECC) recorded that UK consumed 39.68 M tonnes of coal in power generation in 2009 (DECC 2010b. *Digest of United Kingdom energy statistics (DUKES)*. *In:* MACLEAY, I., HARRIS, K., ANNUT, A. (ed.) Department of Energy & Climate Change. TSO: London. Available: http://www.decc.gov.uk/en/content/cms/statistics/publications/dukes/).

and the displaced coal capacity should be used in the transport sector (with CCS technology) to make further GHG emissions reductions.

2. The same sequence applies to the introduction of nuclear and renewables alternatives when coal has been phased out from use in the power sector and replaced by NG.
3. When fossil fuels are phased out from the power fuel mix the excess uranium and renewables resources are directly used in the transport sector in displacement of any remaining oil based fuels. Uranium and renewables are not much different in terms of GHG emissions and the displacement of one another in the power sector does not increase the global reduction in GHG emissions.

7 Standard Results into Perspective

7.1 Introduction

Whilst the World is urged to act on major threats to Mankind such as the global warming and energy security the birth of a roadmap that stands out and presents the solution is not seen. This leads to the question: Why until today have one not been able to develop a viable roadmap? The answer to this question stems from the discussion in Chapter 1 which illustrated how experts disagree in principle over the future of the transport system. In fact there is no common vision to build on and no consensus on what type of technology will prevail. As said by Peter Wells, the co-director of the Centre for Automotive Industry Research at Cardiff University in Wales, for The New York Times in the 2010 Geneva Motor Show: *"Right now, car companies don't quite know what technology to bet on"* (Ewing, 2010).

Nevertheless, today many countries are compiling roadmaps in many cases with specific numerical targets for the advancement of green technologies before resolving the major controversies. As one potent example, Japan's Ministry of Economy, Trade & Industry has set a target of 5 million hydrogen fuel cell vehicles plus 10 million kW for the total power generation by stationery fuel cells by year 2020 (Edwards *et al.*, 2008). There is also Former President Bush's Hydrogen Fuel Initiative which was announced in 2003 with a total budget of $2.1 billion (Kevin, 2006). It will be contended that this is a result of giving most of the attention to the apparent benefits of hydrogen which are promoted by many publications, meetings and exhibitions, though many others have opposing views. The odds of success in this type of proactive action are very low because the roadmap is not built on a well founded framework.

As mentioned earlier in Chapter 1, the difficulty in resolving some of the controversies is seen as being due to the variations in the modelling elements and the individualism in the life cycle analysis of prospective fuel alternatives. These factors not only affect the comparability of the results, but also their usability in strategic planning. Now, if one neutralizes the interventions due to the variations in the modelling elements and perspectives one can generate results that are agreed upon by the experts in the field and thus generate a robust framework that is not affected by such interventions. A framework of such foundation provides a consensus which answers a very important question and that is: What are the true options of tomorrow? Thus the roadmap should only be a progressive result of a well founded framework which strongly presents the

short to long term options of tomorrow and forms the corner stone in building a roadmap for the implementation of these options and the progressive carbon and energy reduction in transport.

In this chapter the author presents a new scenario building approach which is not based on arbitrary targets but rather on a robust framework that was made possible by the STM concept. The scenario building is the first phase in the development of a roadmap and represents a sketch of the future. Nowadays scenario building is commonly done by setting arbitrary targets in the future (e.g. 50% CO_2 reduction by 2050) and building technology/policy packages to meet those targets. The process of building technology/policy packages for the future to meet the target of a certain point in time is called 'backcasting'. The backcasting study approach has been used widely in a number of European projects, such as the OECD EST project (Wiederkehr *et al.*, 2004), the EU-POSSUM project (Banister *et al.*, 2000) and recently the visioning and backcasting of UK transport policy (VIBAT) project which examined the possibility of reducing UK transport CO_2 emissions by 60% by 2030 as part of the Department for Transport's Horizons Research Programme 2004/06 (Hickman and Banister, 2007).

The VIBAT project involved three main stages: (i) setting targets for 2030 and forecasting the business-as-usual situation, (ii) describing the transport system in 2030 that will meet the reduction target, and (iii) backcasting where alternative packages are assembled to lead to the images of the future. In fact the packages assembled in the VIBAT project include not only policy clusters but also technological changes and alternative fuels. However, the options of the future together with their maximum contribution and sequencing in terms of when implementation should take place is governed by the viability of the chosen technology, resource limitations and synergies with other major sectors of fuel consumption. Given the fact that before the STM there was no consensus on the viability of different options it is contended that the images of the future in the scenario building approach that is adopted by the above mentioned projects are desired rather than scientifically founded in a robust manner.

This study has developed and adapted a new scenario building approach in which the images of the future are not desired but rather envisioned by a framework that not only presents a consensus on the true options of the future but also, where applicable, takes into account the synergies with the power sector and the resource limitations. Such a framework is a progressive

result of the STM output analysis and the analysis of the synergistic behaviour between the power and transport sectors in Chapters 5 and 6, respectively.

The following figure shows the stages of the scenario building process developed and adapted in this study:

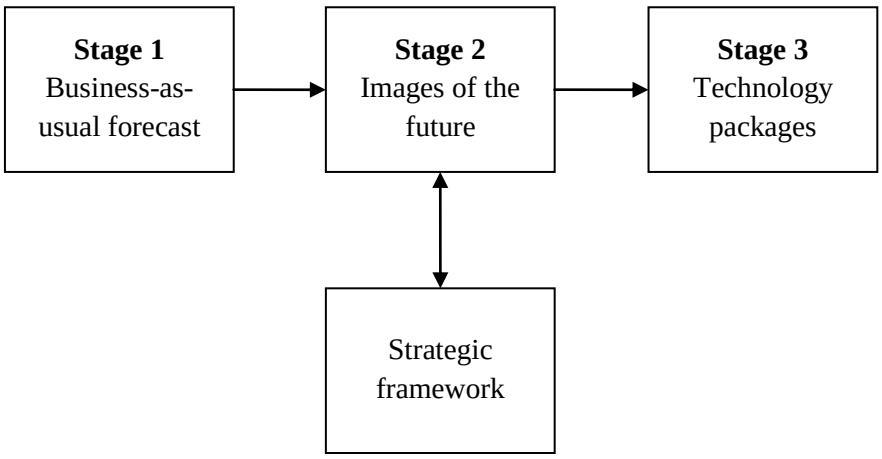


Figure 7.1: The current study approach

Having developed a serious of framework scenarios the effect of the progressive implementation of these scenarios with time is scaled relative to the business-as-usual scenario during the period of effect from the base year to the forecast year. The outcome would answer important questions such as: (i) Can alternative fuels, hybrid technology and carbon capture technology (CCS) bring a certain amount of CO_2 emissions savings (e.g. 60% from the base year) by a specific year in the future (e.g. 2030)? (ii) What would be the shape of the future in a nuclear free World? It can be seen that in the current initiative one seeks the know "What" and the know "Can" and therefore the outlook is on the potential that the future is holding and not on what is desired to happen in the future to meet a specific target.

7.2 Strategic framework

The current section assembles the outcome of the results analysis in the previous two chapters into a strategic framework which acts as the source of vision in the scenario building process as shown in Figure 7.1. Table 7.1 lists the alternatives (technology, fuel, etc) that constitute the framework and shows how they progress with time.

Short term deliverables (post 2010)	Medium term deliverables (post 2030)	Long term deliverables (post 2050)
Hybrid electric petrol cars (CG IC HEVs)	Sugarbeet-based ethanol from near-distance with strict regulations imposed over the farming of sugarbeet and the fermentation process to optimize the land use change emissions, N_2O emissions from fertilizers use and CO_2 emissions from fermentation	Renewables electricity fuelled BEVs
Sugarcane-based ethanol from overseas with strict regulations imposed over the farming of sugarcane and the fermentation process to optimize the land use change emissions, N_2O emissions from fertilizers use and CO_2 emissions from fermentation	Ethanol indirect fuel cell vehicles (FCVs) (with FCVs as compared to ICEVs larger GHG emissions savings are guaranteed and there is higher potential for large savings in excess of 200g of CO_2 equivalent)	
Ethanol ICEVs	LH2 from waste biomass (e.g. forest residue) by gasification with the implementation of CCS technology	
Coal electricity fuelled BEVs with the implementation of CCS technology	CGH2 from waste biomass (e.g. forest residue) by gasification in a decentral system	
	NG electricity fuelled BEVs with the optional implementation of CCS for much larger savings (without CCS the implementation of state-of-the-art CCGT power plants is important)	

Table 7.1: Framework deliverables

In the short term only coal electricity can be used in the transport sector to maximize the reduction of global GHG emissions and maintain security of upstream energy supply, as explained in Chapter 6, and currently BEVs are not widely accepted due to the limitations of the driving range and recharging time. In the medium term when the power sector is clean from coal, the NG electricity can be used in the power sector and BEVs are envisaged as having been developed to become state-of-the-art technology. In the long term the production of biofuels from cultivated biomass (i.e. sugar) phases out to free land and avoid competition with the expanding food markets, the transport sector is cleaned from fossil fuels and the renewables electricity predominate the transport fleet with a minor role for hydrogen FCVs. Thus the ultimate economy is a renewables based electron economy with a minor role for hydrogen in the transport sector and the support of nuclear power in the power sector. More details on the strategic framework are given in the description of the scenarios in Section 7.4.

7.3 Methods

The first stage in the current study is defining a baseline and deriving projections to the future forecast year. In doing so historical data published by the Department of Transport (DfT) in Transport Trends 2009 (DfT, 2009) has been used.

7.3.1 Historical data

In line with the restriction of the STM to passenger cars at the downstream of the various transport options under study, the scope of the current analysis is limited to passenger cars transport which according to the latest figures by DfT forms the big majority of road transport. According to Transport Trends 2009 (DfT, 2009) the passenger cars formed 78.2% of the total road transport in 2008.

The historical data of road traffic by mode is made available in Transport Trends 2009 (DfT, 2009) from 1980 to 2008. The traffic size by passenger cars (cars and taxis) is expressed in billion vehicle kilometres. Given that the latest year of transport statistics made available in the DfT report is 2008, the baseline year of the current analysis is defined accordingly and the traffic size of passenger cars in that year (401.8 billion vehicle kilometres) is set as the baseline for the forecast.

7.3.2 Traffic forecast

The forecast year in this study is 2080 with the intention that the World should become carbon free before 2080. In fact the current concentration of CO_2 in the atmosphere is 387.2 ppm (ESRL-NOAA, 5 November 2010) and the target posed by the leading NASA climate scientist James Hansen in the "Target Atmospheric CO_2: Where Should Humanity Aim?" if humanity wishes to preserve a planet similar to the one on which civilization was developed is 350 ppm at most (Hansen *et al.*, 2008). In terms of cumulative emissions this means that the World is allowed only 350 GtC between 2010 and 2050 with a sequestration of further 150 GtC between 2050 and 2100, if atmospheric CO_2 is to fall to 350 ppm by the end of the century. In a more practical sense the carbon budget of 350 GtC between 2010 and 2050 means that the net global CO_2 emissions will have to decline to zero by 2050 at an annual rate of decline which starts high and soon reaches a steady rate of 10% per year for several decades (Baer *et al.*, 2009).

The method used to forecast the passenger cars traffic growth from the given historical data on the UK traffic trends is the simple exponential smoothening which according to Attaran (1992, p.83) is the most widely used of all forecasting techniques and requires little computation. The equation to calculate an exponential smoothing is:

$$F_t = \alpha A_{t-1} + (1 - \alpha) F_{t-1} \qquad \text{Eq. (7.1)}$$

Where,

F_t: Forecast for the period t

A_{t-1}: Actual value of the time-series in the prior period

F_{t-1}: Forecast made for the prior period

α: Smoothing constant between 0 and 1

The exponential smoothening is a way of weighing the effect of previous observations on the forecast F_t in the sense that the older observations are given relatively less weight than the recent observations. The value of α determines the speed at which the older observations in the historical data are damped (smoothed) such that when α = 1 the weight of the older observations is damped right away and the full weight is given to the most recent observation (A_{t-1}) and when α = 0 the damping is slow.

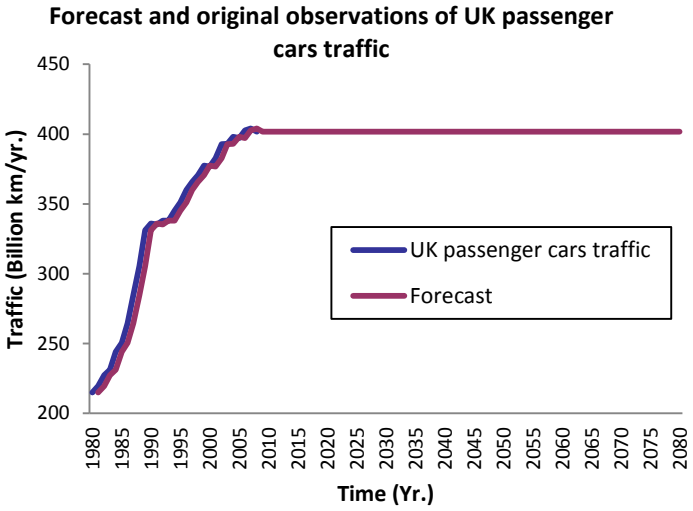


Figure 7.2: The forecast and historical data of UK passenger cars traffic

The software tool used in the current analysis to perform the forecast is StatTools v5.7 (Palisade, 2010b) where α can be optimized to minimize the standard error (root mean square error) which determines the goodness of fit between the forecast trend and the observed trend. At a minimum standard error of 9.46 billion kilometres per year the α value is calculated as 1.00 which states that the forecast value is equal to the most recent observed value. It follows that the difference in the traffic kilometres between one year and the following is very small otherwise the RMS error wouldn't have been very small given from the forecast output that the average percentage absolute error is only 2.27%. Therefore, historical data of this nature will always generate a steady forecast at any point in the time series using the exponential smoothening method and renders the forecast meaningless. For instance, if the forecast was performed in 1995 using the given historical data (1980-1995) the forecast trend would have been steady and that is not what actually happened as seen from the original observations in Figure 7.2. Nevertheless, the forecast trend is adopted in the current study as a target that should be achieved by behavioural changes through a combination of policies and increased public awareness.

7.4 Scenarios

The framework described briefly in Section 7.2 is progressively used to build a set of scenarios each representing a different level of technological restriction. These are described below starting with the complete technology package scenario which represents an optimistic view of the GHG emissions reductions that can be achieved within the forecast period. This is followed by the scaling of the effect of the progressive implementation of these scenarios. The outcome is summarized in Section 7.6.

7.4.1 Complete technology package

In the first decade ethanol based on sugarcane is mainly imported from Brazil. As dictated by the results of the STM in Chapter 5 the implementation of sugar ethanol in ICEVs without strict control over sugar farming as well as the fermentation process results in a high risk of GHG emissions debt. As a matter of fact in strategic planning one tolerates no risk and guarantees some GHG emissions savings before seeking the larger potential savings. Therefore, the implementation of sugar ethanol is tied to strict control over the farming and fermentation processes to guarantee some GHG emissions savings. Later significant GHG emissions savings

can be guaranteed with the implementation of sugar ethanol when second generation bio-vehicles (indirect FCVs) are developed.

Moreover, hybrid technology is on the urge of fast penetration into the transport sector as it guarantees significant GHG emissions savings. In fact recently a global wave of small hybrids for global markets has started. The latest motor show in Paris, Paris Motor Show 2010, displayed practical compact hybrids such as: (i) the Toyota FT-CH which is the leading candidate for beating the Toyota Prius's 50 mpg average fuel economy, (ii) the Lexus CT200h which is another example of Toyota's move to down-size hybrids and could be the first luxury vehicle to average more than 40 mpg, (iii) Honda Jazz Hybrid which is likely to surpass the other Honda hybrids such as the Honda Insight and CR-Z hybrids and is another candidate for the 50 mpg club, and (iv) the Ford C-Max among which the Grand C-Max model will likely become the most fuel efficient seven-seat vehicle on the market (hybridcars.com, 2010).

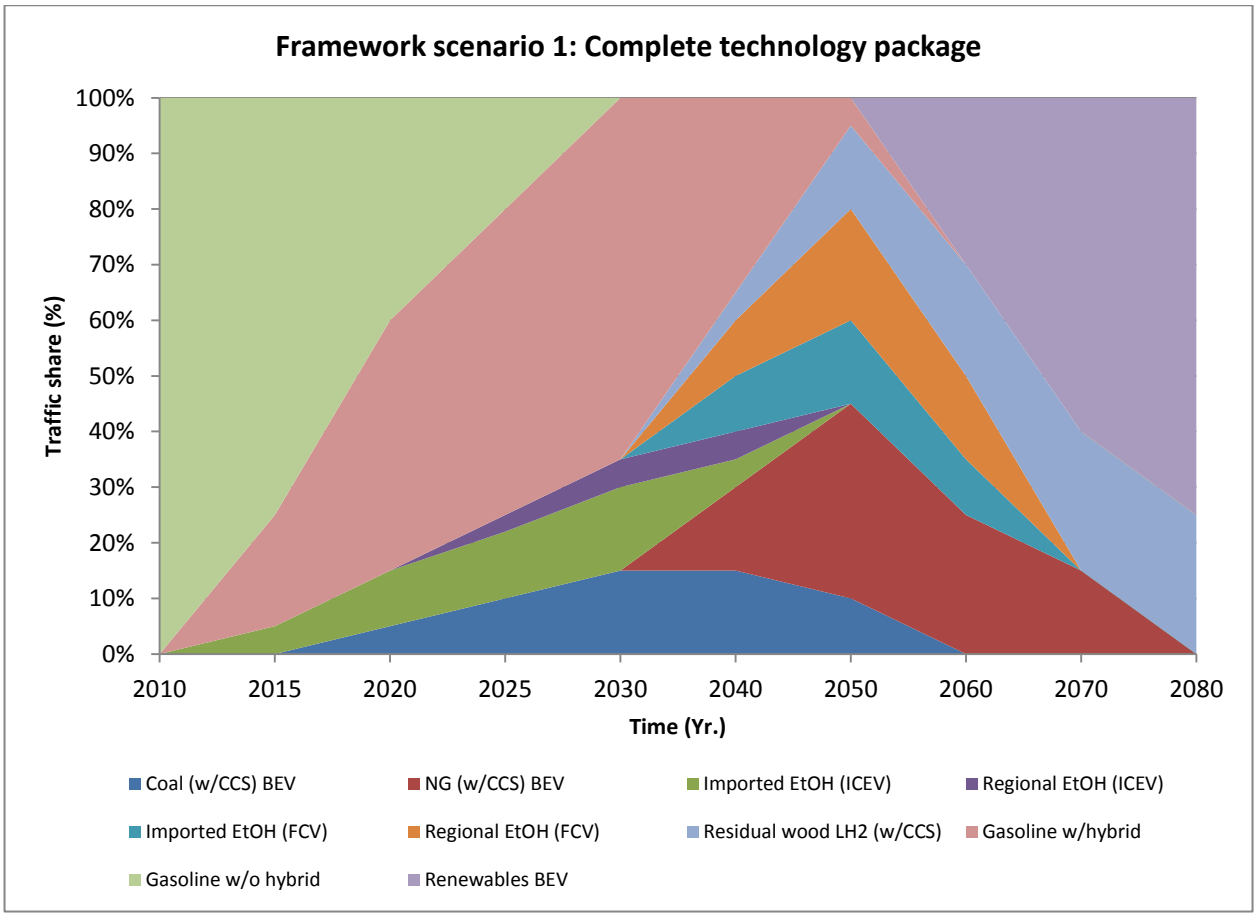


Figure 7.3: The area chart of scenario 1 showing the contribution of different deliverables (i) at any point in the time series and (ii) over any time period within 2010-2080

As shown in Figure 7.3 above according to the facts about hybrids development the hybrid petrol cars are assumed to directly penetrate the market at a high rate to acquire 20% share in 2015 and 45% share in 2020. In fact all-electric cars are also seen moving from prototypes to near term production. Among the all-electric cars that were on display in Paris Motor Show 2010 the following are mentioned: (i) the Citroen Sorvolt which is powered by a 300 hp (horse power) dual electric motor and can travel 193 km on a charge from its 31 kWh battery pack, (ii) the Saab 9-3 SportCombi EV Wagon which is powered by a 181 hp electric motor and can travel 193 km on a charge from its 35 kWh battery pack, and (iii) the Volvo C3 EV which promises 160 km on a charge (Popular Mechanics, 2010).

However, in the short term penetration of all electric cars into the transport sector there are some problems other than the technical and economic feasibility. Actually the type of refuelling electricity is very important in the account. As mentioned in Chapter 5 “the reliance upon BEVs will be detrimental if the electricity is coal based without the implementation of CCS technology.” In fact even with the implementation of CCS technology there is no guarantee of GHG emissions savings. Moreover, with the clean coal technology (IGCC) in addition to the CCS technology the guaranteed savings is still not significant. Therefore, in the implementation of BEVs driven by coal-based electricity while necessarily integrating the CCS technology one does not guarantee much GHG savings but seek the larger potential savings. On the other hand, the fuelling of BEVs with more clean power alternatives such as NG, nuclear or renewables based electricity is not allowed before coal is phased out from use in the power sector which includes the residential, commercial and industrial sectors of power demand. The later restriction was explained in Chapter 6 under the study of the synergistic behaviour between the power and transport sectors. The neglect of factors external to the transport system will result in a significant slowdown of the global reduction in GHG emissions but Mankind has only a limited time to act against the disastrous effects of Global Warming. As seen in Figure 7.3 above the contribution of BEVs in the first decade is low because of the time required to develop and implement CCS technology and the technical and economic limitations of BEVs. In fact BEVs only start penetrating the market in 2015 when it is believed that the first clean coal power plant with CCS technology starts operating and BEVs become adequately commercial.

In the second decade the rate of increase in the dependence on imported ethanol is reduced while an economically viable system for regional sugarbeet-based ethanol is developed to increase the

contribution of biofuels to the green fuels mix. Nevertheless, strict control over the farming of sugarbeet and the fermentation process should be maintained to eliminate the possibilities of GHG emissions debt. Also the hybrid electric cars continue to acquire a greater share of the petrol car fleet while the technology is developed and becomes more economically competitive, and the non-hybrid petrol cars are completely phased out.

Around 2020 (depending on how well one performs on the commissioning of nuclear plants) nuclear electricity substitutes for much of the coal used in the power sector and decreases reliance on NG. This continues until 2030 when the power sector should be clean from coal with the remaining coal-fired power plants supplying electricity to the transport sector. Thus following 2030 the use of NG-based electricity to drive BEVs does not incur indirect GHG emissions in the power sector and comes streaming with the continued clean up of the power sector from fossil fuels and the technical and economic improvement of BEVs. In the phase before 2030 the dependency on the nuclear power is heavy and compensates for the slow growth in renewable technology (wind, hydro, etc). In fact from the past trends of renewable technology development one should not expect much contribution in the future. The major barrier that is forbidding the exploitation of the enormous amounts of renewable energy is technology. Therefore, what the World really needs is not a business-as-usual development of renewable technology but a technological breakthrough in the methods of harnessing renewable energy.

In the third decade (2030-2040) the supply of sugar ethanol from overseas is maintained while the regional market develops to acquire more share of the transport fuel mix. The second generation ethanol vehicles (ethanol FCVs) inexorably penetrate the market acquiring two thirds of the ethanol-fuelled fleet. On the other hand, the hydrogen starts to play a minor role in the market through the development of liquid hydrogen (LH2) centralized systems which implement the CCS technology in the conversion of the valuable biomass waste (e.g. forest residue) into a transportation fuel by gasification. Such a minor role of hydrogen does not justify the huge investments required to build an infrastructure for gaseous hydrogen (CGH2) centralized systems. Therefore, at this stage large amounts of energy loss in hydrogen liquefaction are traded for bypassing the huge investments required for the development of a hydrogen distribution infrastructure. Also the contribution of petrol cars starts to significantly phase out with the development of the alternative fuels such as ethanol and electricity.

Most important, the beginning of this decade marks the onset of a technological breakthrough in renewable technologies that allows for wide implementation. The steep penetration of renewable technology displaces NG in the power sector and decreases reliance on nuclear power in displacing NG. Concurrently, the use of BEVs in the transport sector increases significantly with the improvement of the technical and economic feasibility of all-electric cars and their acceptance by the consumer.

The fourth decade (2040-2050) will witness a slowdown in the development of biofuels production as the set aside, marginal, and degraded land becomes scarce (see Figure 5.18 in Chapter 5). Nevertheless, the regional ethanol market continues to grow but at a slower pace. Further, the ethanol ICEVs completely phase out from the market as the ethanol FCVs continue to develop and acquire market share. On the other hand, the share of hydrogen fuel continues to grow while one benefits from the unmatched GHG savings that this system provides (see Figure 5.22 in Chapter 5). Also the phasing out of petrol cars accelerates as the alternative fuels market significantly develops. Finally, the use of coal-based electricity in the transport sector starts diminishing with the decommissioning of the installed capacity and the contribution of NG-based electricity significantly increases with its displacement in the power sector and the further development of all-electric cars.

In the fifth decade (2050-2060) the demand for biofuels starts competing with the demand for food and the production of biofuels starts declining to free land for food production. This decade marks the beginning of a new era in transport which witnesses the phasing out of petrol cars that dominated the old era which lasted for more than a century. Furthermore, the share of hydrogen fuel continues to grow based on the biomass waste that does not interfere with the food/feed markets. Also, the growth of renewable electricity accelerates as the renewable technology becomes state-of-the-art and the development of nuclear capacity supports the penetration of electricity into the transport sector at a very high rate. Here it is important to note that the reliance on nuclear electricity in the power sector may increase again after being offset in the third decade to support the penetration of renewable electricity into the transport sector.

In the sixth decade (2060-2070) the production of biofuels from cultivated biomass is phased out due to the synergy with the food markets and the share of hydrogen fuel grows to the maximum that the capacity of local waste wood allows. Moreover, the renewable electricity inexorably

penetrates the transport sector while the last share of fossil fuels almost phases out with the decommissioning of the installed capacity.

In the last decade (2070-2080) the share of hydrogen fuel remains constant while the growth of local waste wood capacity is limited. The most important mark of this decade is the realization of the "electron economy" which is based on renewable electricity (with nuclear support in the power sector) and involves a minor role for hydrogen.

7.4.2 Nuclear free World

Nuclear power was a focal point in scenario 1 and largely affects the shape of the future transport fleet; it plays a major supporting role in cleaning up the power sector from fossil fuels and the penetration of the renewable electricity into the transport sector. The question that policy makers will have to address is: What will be the shape of the future in a nuclear free World?

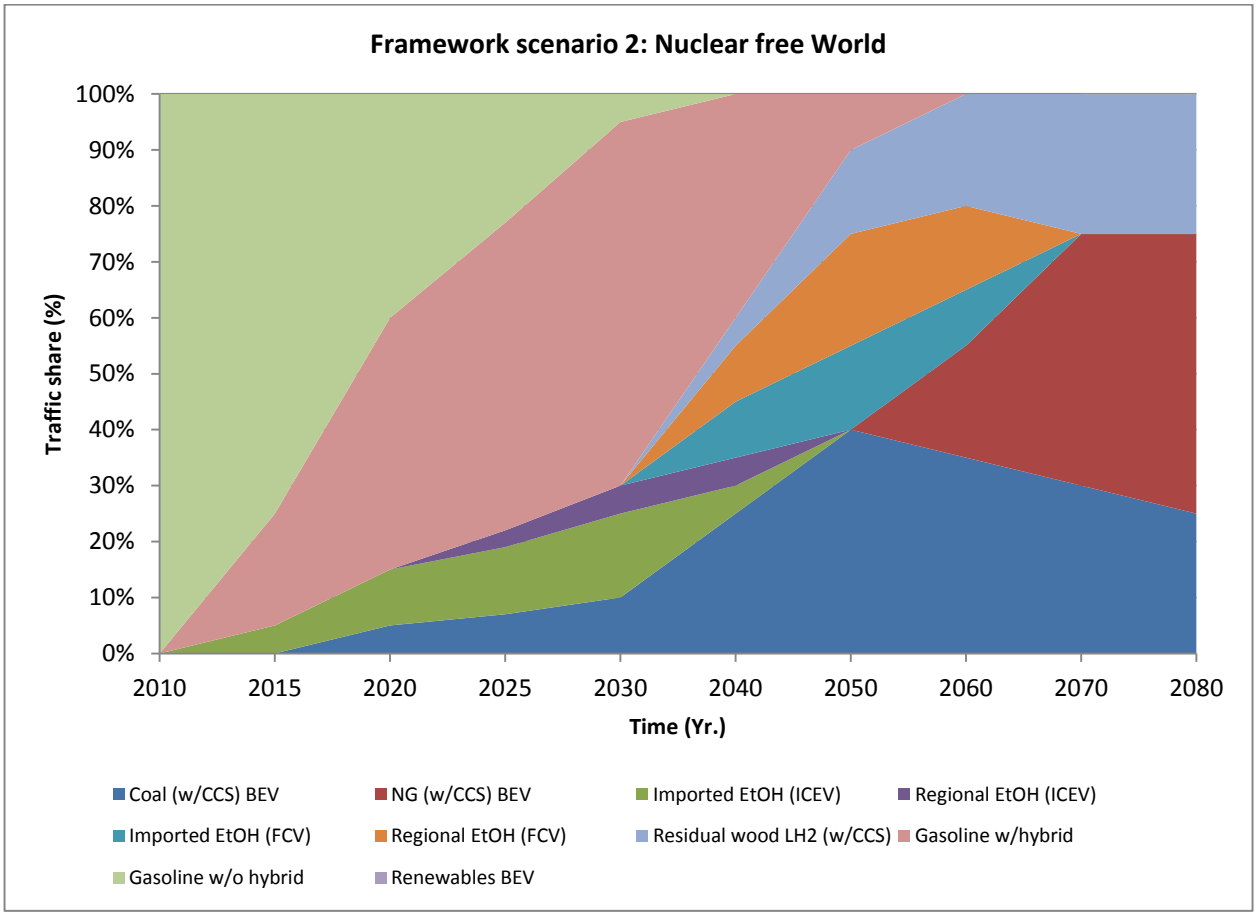


Figure 7.4: The area chart of scenario 2 showing the contribution of different deliverables (i) at any point in the time series and (ii) over any time period within 2010-2080

In the first phase (2010-2030) NG displaces coal in the power sector on a limited basis as permitted by the upstream supply. The penetration of the coal fuelled BEVs into the transport sector moderately increases with the technical and economic improvement of BEVs; nevertheless this most likely implies an increase in the coal power capacity because NG supply is not likely to increase fast enough to compensate for the coal used in the transport sector. The cleanup of the power sector from fossil fuels only begins in the second phase (2030-2050) which marks a technological breakthrough in renewable technologies. The use of BEVs in the transport sector significantly accelerates with the implementation of renewable technology and the further improvement of the technical and economic feasibility of BEVs. In two decades from the breakthrough of renewable technologies the power sector is clean from coal and NG starts supplying the transport sector with electricity. The supply of the NG-based electricity to the transport sector continues to grow with the cleanup of the power sector while the supply of the coal-based electricity declines slowly to allow compensating for ethanol as it is phasing out. The cleanup of the power sector from fossil fuels is much slower as compared to scenario 1 where renewable electricity is supported by nuclear power. Therefore, it is not expected that until 2080 does the renewable electricity supply the transport sector. Moreover, despite the state-of-the-art renewable technologies at that time with no support from the nuclear power the cleanup of the transport sector from fossil fuels is slow. As such under this scenario the electron economy is not expected to be realized before 2100 if realized at all.

7.4.3 Renewables breakthrough only

The absence of nuclear power and CCS technology will exclude coal electricity from the deliverables list and will delay the role of BEVs until the third phase only when the power sector is cleaned from coal after the wide spread implementation of the renewables technology in the second phase. Actually the role of NG in displacing coal in the power sector during phase I and II is limited by the upstream supply security. Nevertheless, the wide implementation of renewables technology in the second phase will decrease reliance on NG and in the third phase will displace NG allowing its fast term penetration into the transport sector. Furthermore, the use of NG electricity in the transport sector in the absence of CCS technology is tied to the state-of-the-art CCGT power plants to guarantee some GHG emissions savings. In fact although this scenario is based on the breakthrough of renewables technology, renewable electricity will not make it into the transport sector before 2080.

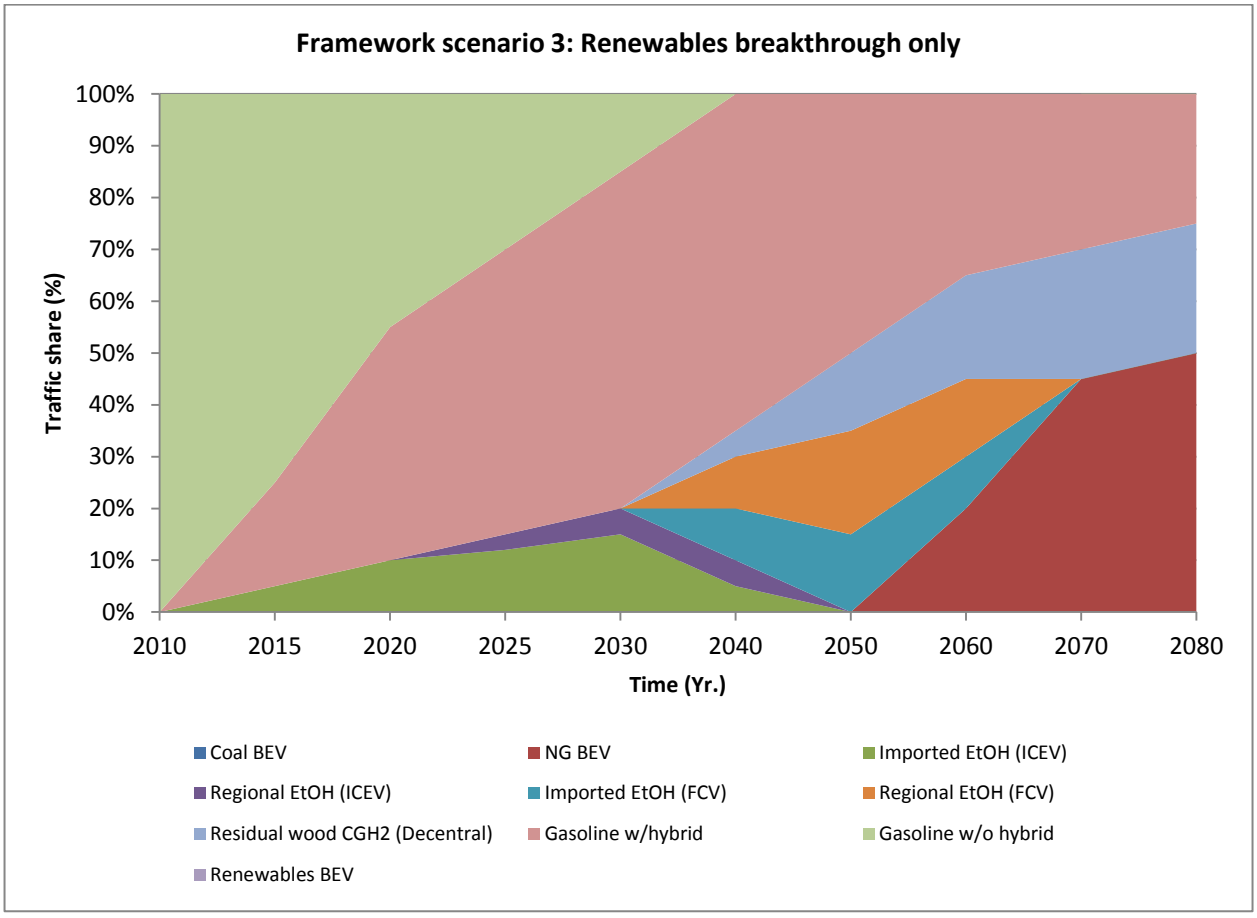


Figure 7.5: The area chart of scenario 3 showing the contribution of different deliverables (i) at any point in the time series and (ii) over any time period within 2010-2080

As seen in Figure 7.5 above, in the absence of both nuclear power and CCS technology the passenger cars fleet in 2080 is still predominantly fuelled by fossil fuels.

7.4.4 Nuclear only

In this scenario although nuclear power is present the coal electricity cannot be used in the transport sector in the absence of CCS technology. Moreover, after cleaning the power sector from coal in the first phase the contribution of nuclear power does not grow much further as there is a limitation to the level of nuclear power proliferation that is acceptable to the society. In fact nuclear power can play a major supportive role however it cannot be widely exploited such as fossil fuels and renewables. Therefore in the second phase the NG electricity remains alongside nuclear electricity in the power sector and its use in the transport sector is limited to levels that do not jeopardize the security of upstream supply. The result is that the role of BEVs is not only delayed but is permanently limited; it is only until 2060 when the business-as-usual development of renewables is expected to make a small difference and smoothly decreases

reliance on NG in the power sector which allows for more NG to be used in the transport sector. Nevertheless, the BEVs contribution would remain much limited. As compared to scenario 3 the limitation of BEVs in this scenario implies much more role for petrol cars remaining until 2080. As seen in Figure 7.6, in 2080 the petrol cars still acquire the largest share of the market and BEVs only have a 15% share.

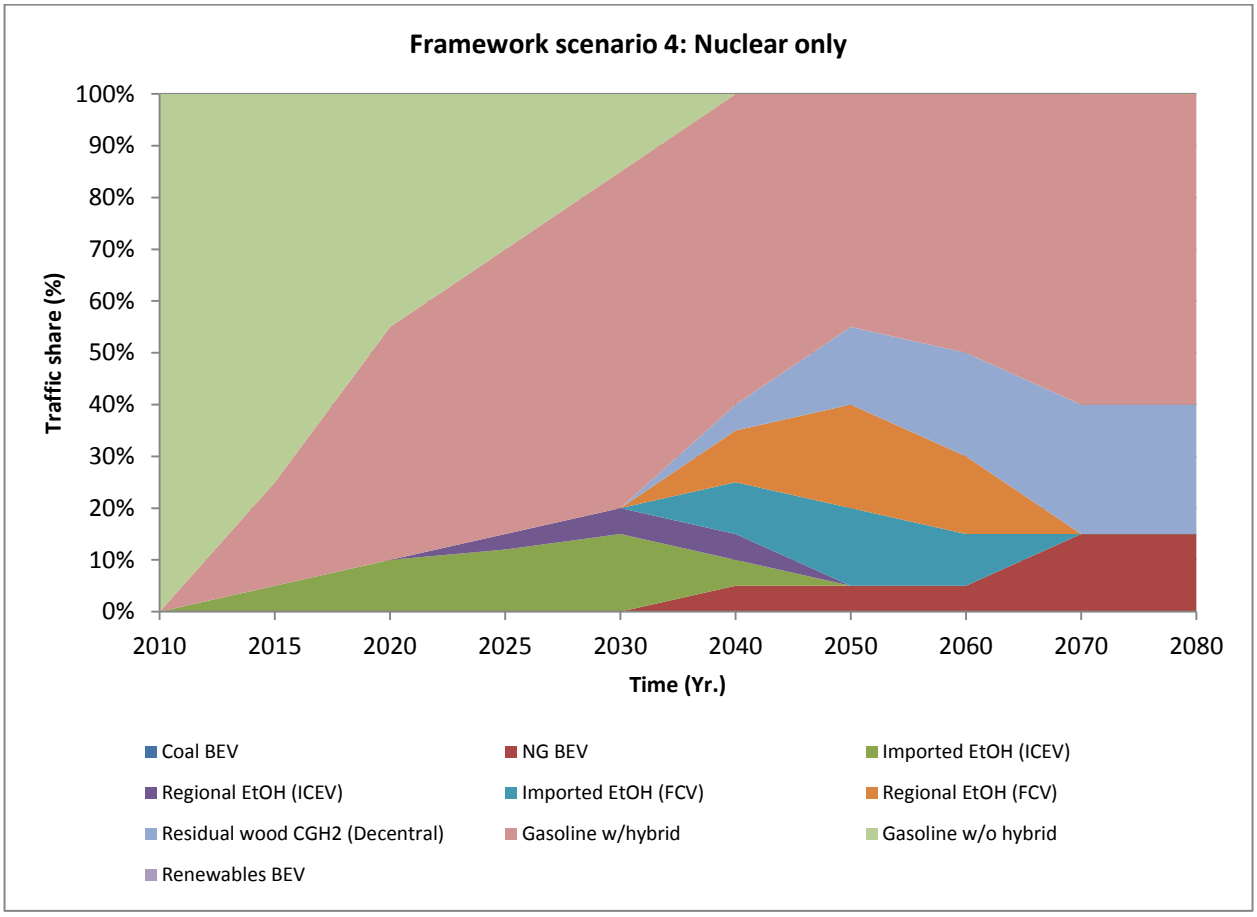


Figure 7.6: The area chart of scenario 4 showing the contribution of different deliverables (i) at any point in the time series and (ii) over any time period within 2010-2080

7.4.5 All technology except renewables breakthrough

As policy makers tend to assume a renewables breakthrough at some point in the future they have to address the question: What will be the shape of the future if a renewables breakthrough was unfortunately not achieved? A scenario of the future without a breakthrough in renewables was presented in the previous section; however the difference in this section is the implementation of CCS technology. In this scenario much more reliance is placed on coal-fuelled BEVs to displace petrol cars. The implementation of CCS technology allows the use of

coal in the transport sector as it is phased out from use in the power sector with the development of the nuclear power. However, given that in this scenario one ends up relying much more on coal while NG use in the transport sector is limited one have to address whether the progressive implementation of coal w/CCS in the transport sector will actually bring GHG emissions savings. In fact caution is required because the scale of the effect of coal w/CCS implementation in the transport sector using the median value of the STM result may be optimistic; the potential GHG emissions savings are not guaranteed.

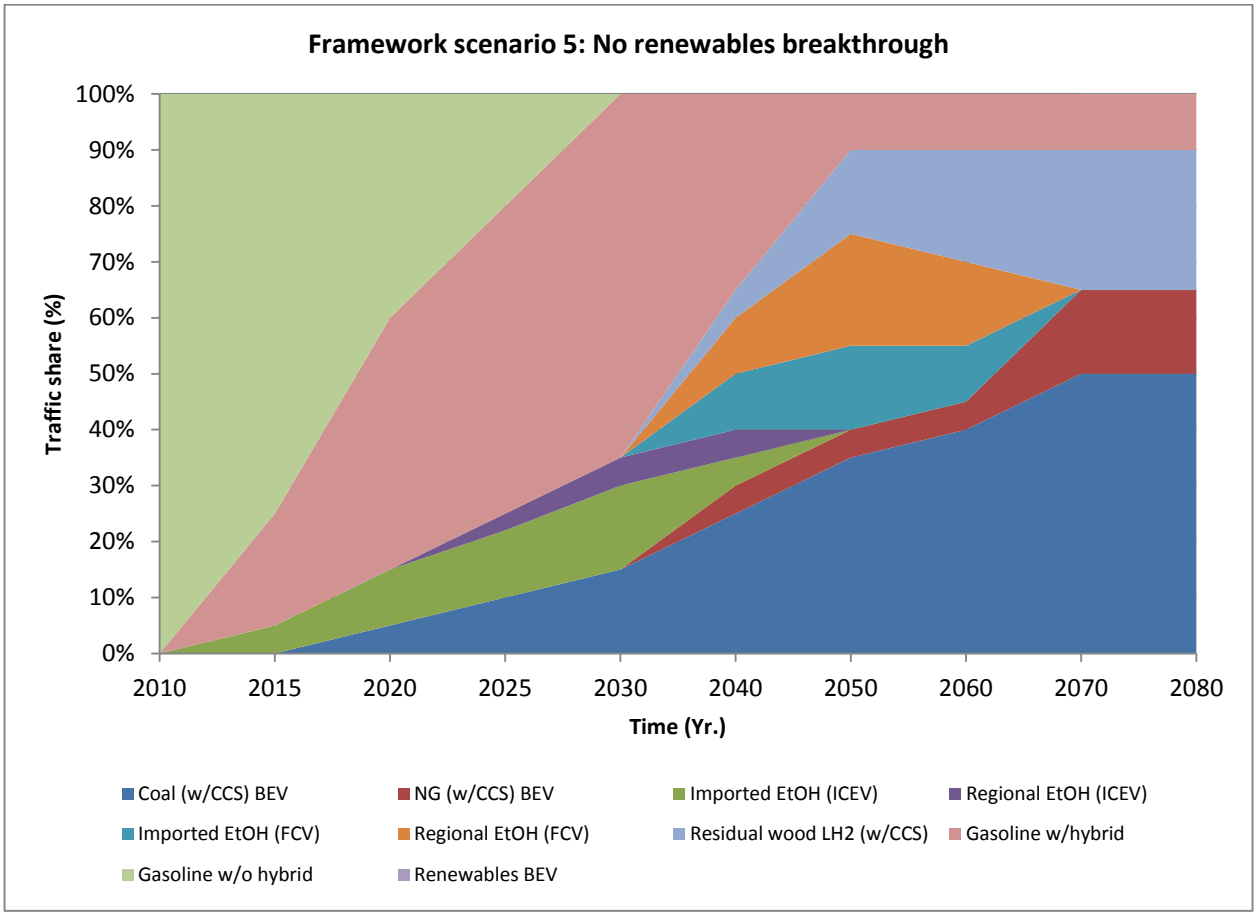


Figure 7.7: The area chart of scenario 5 showing the contribution of different deliverables (i) at any point in the time series and (ii) over any time period within 2010-2080

7.4.6 All technology except CCS

In this scenario coal use in the transport sector is excluded with the absence of CCS technology and the role of BEVs is delayed until the second phase. Also the NG use in the transport sector will bring much less GHG emissions savings. The overall effect of the absence of CCS technology is the decrease of the cumulative GHG emissions reduction achieved within the

scenario interval from 2010 to 2080. Nevertheless, this scenario confirms the important role of nuclear as supplementary to renewables where the absence of CCS technology does not affect the wide implementation of renewable electricity in the transport sector and the realization of the so-called electron economy.

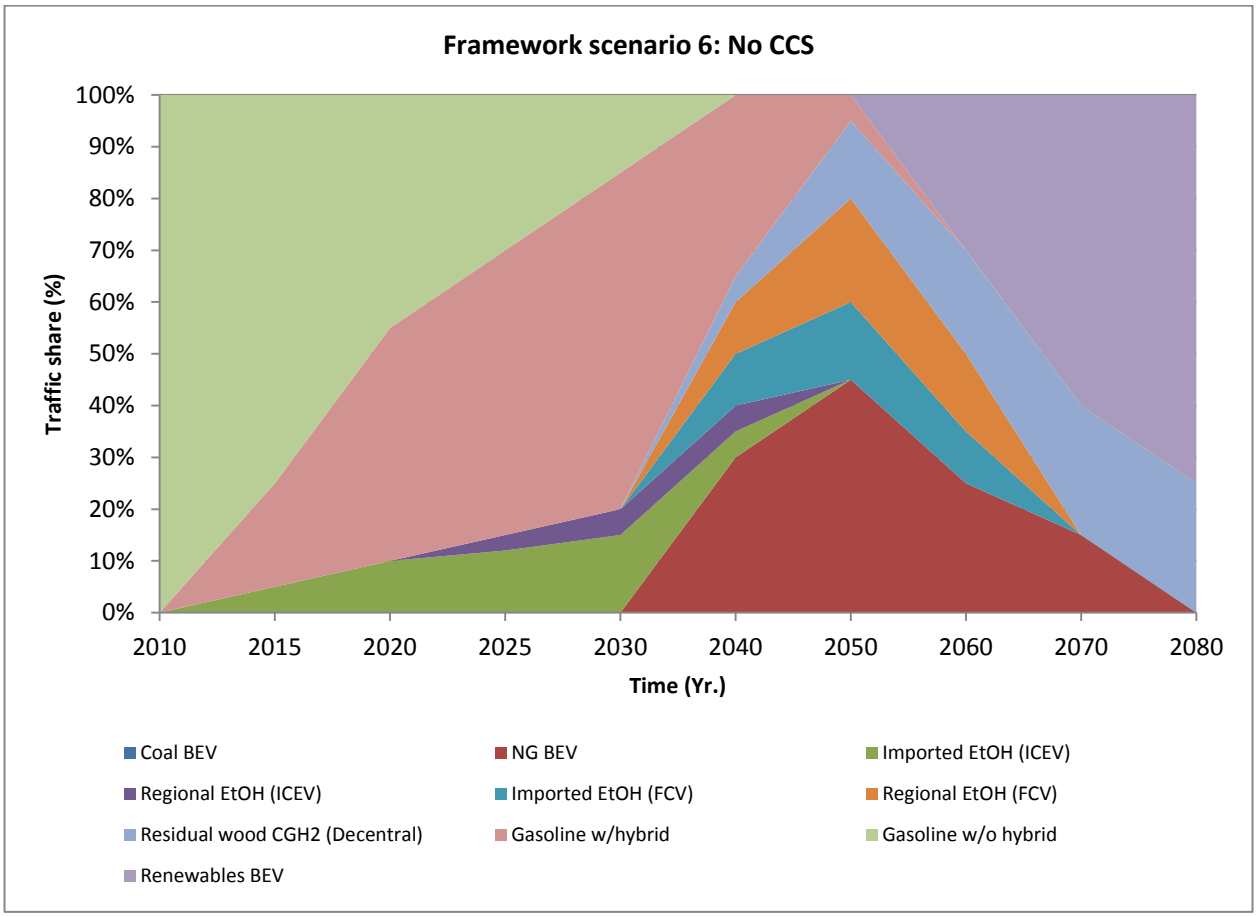


Figure 7.8: The area chart of scenario 6 showing the contribution of different deliverables (i) at any point in the time series and (ii) over any time period within 2010-2080

7.5 The scale of effect

In this section the effect of the progressive implementation of the framework scenarios that were described in the previous section are scaled. The scaling is done relative to the business-as-usual scenario which is shown in red line in Figure 7.9 and Figure 7.10 below. In fact the aim is to maximize the cumulative reductions in GHG emissions and energy depletion and accelerate the action against Global Warming and energy scarcity. In graphical terms the cumulative reduction is the area bound between the business-as-usual and the framework scenario curves. The data

used to scale the progressive implementation of different scenarios is adopted form the STM results. (The median values were used to balance between pessimism and optimism.)

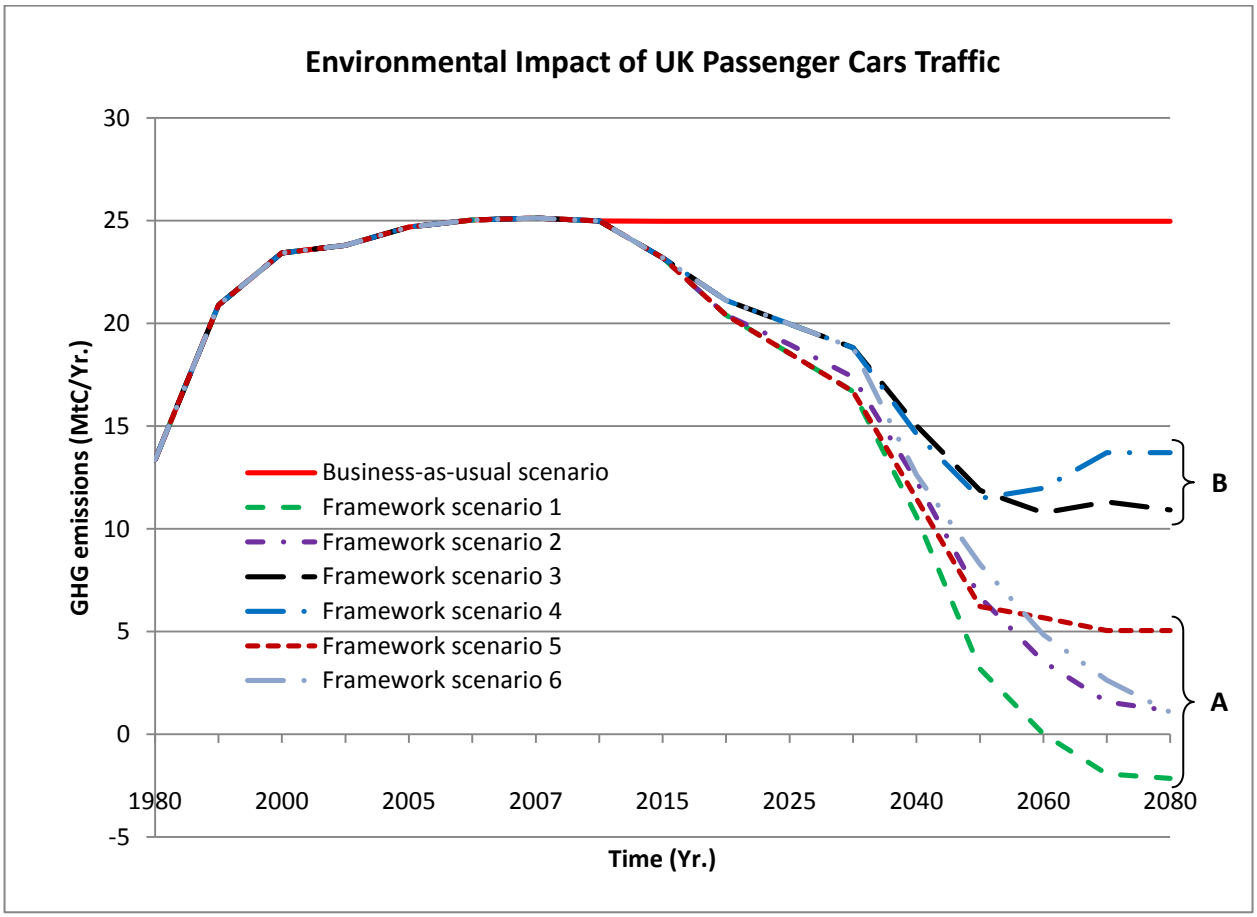


Figure 7.9: The scale of effect on the environment in terms of GHG emissions from the progressive implementation of different framework scenarios

From the results in Figure 7.9 above one can interpret that the most important deliverables to the transport sector are renewable electricity and CCS technology. The group B scenarios which result in much less cumulative GHG emissions reductions as compared to the other scenarios represent no CCS and no renewable electricity penetration into the transport sector. In both scenarios 3 and 4 no CCS is assumed. Moreover, although a renewables breakthrough is assumed in scenario 3 the absence of nuclear power in the power sector implies that renewable electricity will not make it into the transport sector within the foreseen period. This further emphasizes the importance of nuclear power as a support to the renewables penetration into the transport sector. On the other hand, the scenarios of group A represent CCS and/or renewable electricity penetration into the transport sector among which scenario 1 with its complete technology package results in the largest cumulative reduction in GHG emissions. The sinking of carbon

beyond 2060 is a result of the waste wood gasification central systems which incorporate CCS and generate very large *negative* GHG emissions. The other scenarios such as 2, 5 and 6 do not benefit from the fortune of CCS technology and renewables electricity together as either of the two deliverables is absent.

Nevertheless, it is noticed that in the absence of renewable electricity and the presence of CCS technology which largely cleans the fossil fuels systems from CO_2 emissions the reliance on fossil fuels can be increased and the result is similar to a scenario with the opposite where renewable electricity penetrates the transport sector and CCS technology is absent. Therefore even without the renewable electricity penetration into the transport sector one can perform pretty well by cleaning up fossil fuel systems using CCS technology. However, the achievement of a breakthrough in renewable technologies is still important. As seen in Figure 7.9 beyond 2050 scenarios 2 and 5 do not move together although both represent no penetration of renewable electricity into the transport sector. In fact both scenarios 2 and 5 result in the predomination of fossil fuels however the advantage of scenario 2 over scenario 5 is a result of the renewables breakthrough in scenario 2 which is absent in scenario 5; where the limitation of nuclear power proliferation in scenario 5 limits the use of NG in the transport sector (see Section 7.4.5) the renewables breakthrough in scenario 2 allows a much wider use of NG in the transport sector whilst NG is much cleaner than the alternatives such as coal.

Furthermore, the impact of traffic on the environment is not the only challenge that is tackled with the progressive implementation of the framework scenarios. Although one may disagree on which is more serious, the Global Warming or the scarcity of energy resources, it is agreed that both are serious enough to concentrate our attention. The solution to the escalating depletion of energy resources is straight forward and that is the implementation of as much renewable resources as possible to displace exhaustible energy resources. The consumption of biomass and non-biomass renewables implies no energy depletion because the resource is regenerated in short cycles.

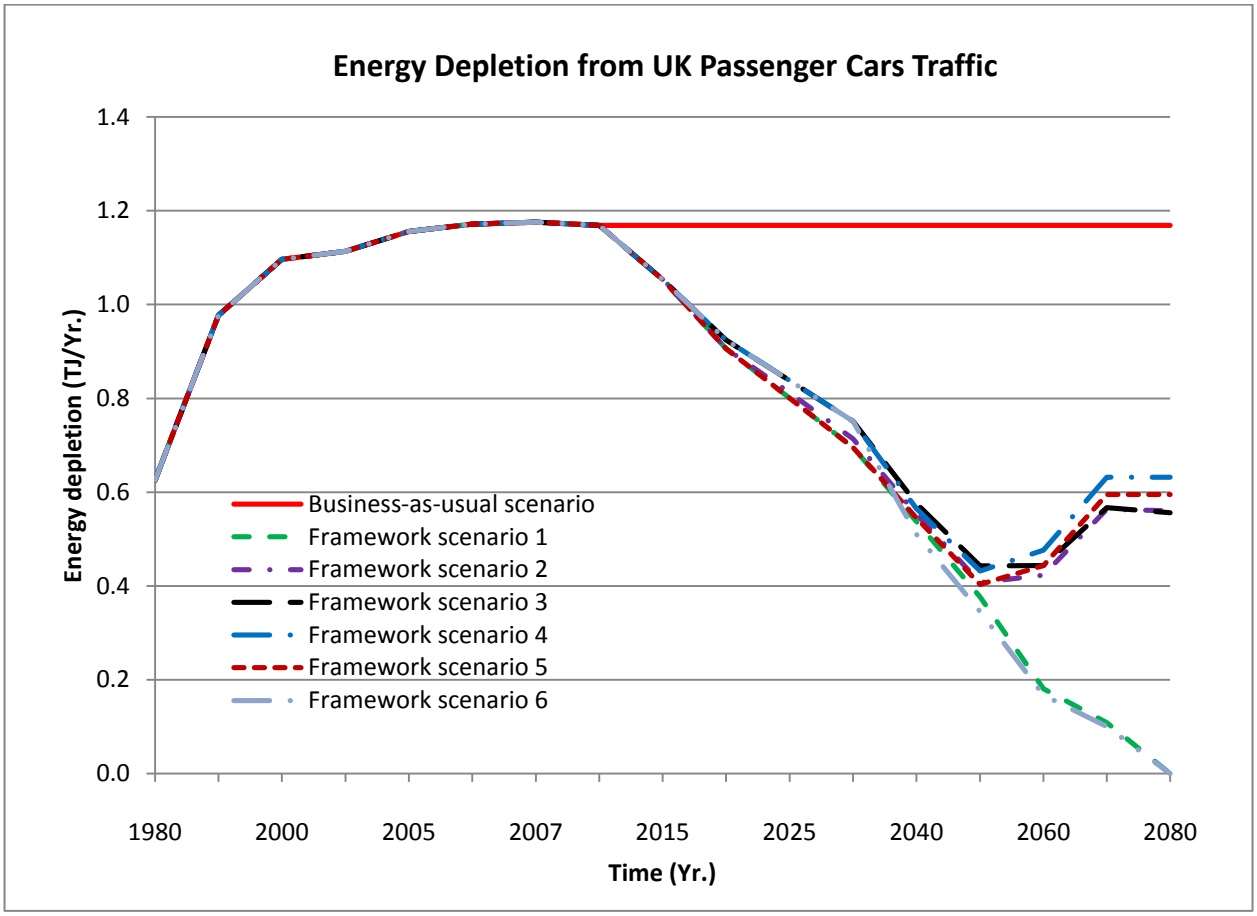


Figure 7.10: The scale of effect on the depletion of energy resources from the progressive implementation of different framework scenarios

As seen in Figure 7.10 above scenario 1 and 6 present the best cumulative reduction in energy resources depletion because besides the implementation of biomass-based systems and non-renewable alternative systems with improved efficiency over the conventional system these are the only two scenarios in which non-biomass renewables widely penetrate into the transport sector beyond 2050.

7.6 Conclusions

In response to the critical situation that is threatening the existence of Mankind in the future the answer to the question of whether it is still possible to save the World from the disastrous consequences of Global Warming and energy scarcity is a preliminary “yes”. The application of the concepts that resulted from the standardization of the major WtW models should move eager nations from the phase of studying options to the phase of building roadmaps and initiating projects. Although the implementation of scenario 1 is very challenging and requires huge

investments coupled with concentrated efforts for the development and implementation of the required alternative systems, the foundation of scenario 1 is realistic and takes into account a reasonable time for the development of BEVs, the development and implementation of CCS technology, the commissioning of the nuclear power plants and the development and exploitation of renewable technologies. The result is zero GHG emissions in the power sector by 2050 and the same in the passenger cars transport by 2060 followed by carbon sinking in the passenger cars transport beyond 2060.

In fact these results are not far away from the goal equivalent to the 350 ppm target that was posed by James Hansen (Hansen *et al.*, 2008) and that is net global GHG emissions of zero by 2050 (Baer *et al.*, 2009). The target posed by James Hansen is the most stringent today and promises to preserve a planet similar to the one in which civilization was developed, though the realization of the goal equivalent to this target for passenger cars transport is not impossible. In fact based on the proposed scenario (scenario 1) with an earlier breakthrough in renewable technologies we can bring the passenger cars transport to zero GHG emissions at least one decade earlier and move in line with the "350" target.

On the other hand, under scenario 1 the passenger cars transport becomes nearly fully sustainable in terms of energy and preserves all the Mega Joules for the future generations. Nevertheless, it is important to note that fossil fuels are not only a source of Mega Joules but a very important source of chemicals. Thus by stopping the depletion of fossil fuels the irresponsible use of this precious resource is stopped.

The important message though is that the different alternative systems in a scenario work synergistically and their optimum strength comes with the complete technology package as in scenario 1. The absence of any of the proposed technologies will significantly affect the performance of the overall scenario.

7.7 Limitations

The limitations in the scenarios presented in this study are: (i) they do not take into consideration the possible interference from the other subsectors of transport such as light duty vehicles (LDVs), heavy goods vehicles (HGVs), aviation and rail. Therefore the work presented in this chapter should be revised to involve any interference from the other subsectors of transport such

as sharing the biomass resources or other capacity of alternative energy, (ii) the scenarios do not take into consideration the commercial viability and economic incentives, and (iii) the current passenger cars transport fleet is assumed to be all petrol driven and thus the small proportion of diesel passenger cars is neglected. Nevertheless, diesel cars are not significantly different in terms of energy consumption and GHG emissions as compared to petrol cars and therefore the assumption of all petrol cars does not notably change the business-as-usual scenario.

8 Summary and Conclusions

8.1 Summary

Following the concerns regarding Global Warming there has been increasing interest in Well-to-Wheel (WTW) assessment of automotive fuels. Such analyses are increasingly required to assess the global implications of prospective transport options for medium to long term futures. The author recognizes the high quality of the WtW models developed by the expert researchers and centres in the field around the World such as Michael Wang, Öko-Institut, General Motors Corporation, Mark Delucchi, Massachusetts Institute of Science and Technology, Ulf Bossel and the Joint Research Council of the European Union. However classic WtW modelling has a major pitfall when it comes to policy making and strategic planning. In classic WtW modelling one assumes a default set of inputs which represent one database and one set of modelling assumptions and choices. Thus this type of modelling does not allow for any variation in the elements of the model such as the type and design of the conversion process, the geographic distance of pipeline transport and the methodological choices, amongst others. On the other hand, it was shown in Table 1.1 and acknowledged in more than one study in the literature that the variation in the modelling elements has a major disruptive effect on the WtW result. Given this, it is unsurprising that there is disagreement in broad principle over important subjects such as the viability of the hydrogen economy and the CO_2 footprint of biofuels. Therefore, although classic WtW models are important measuring tools the single results from such models do not possess the reliability required for strategic decision making. Such results whether stochastic (probabilistic) or deterministic fail to present the actual uncertainty of the output.

The generation of the novel STM, that was introduced herein, rests upon the conviction that there is a need for some synthesis which creates a statistically sound aggregate of the different WtW results from the different models in the field as it would be irresponsible to base a strategic decision on just one study or model. Such an aggregate WtW result is the first of its kind to present the complete as possible picture about the option under study. The STM combines the different models in the field at each stage of the WtW chain including models of different expert groups as this is important to build up large reliability in the output result. The effect of standardization from the reliability perspective can be seen in two ways: (i) the combination of the modelling elements of the different models of the major expert groups smoothes the standing of single individual assumptions, choices and parameters and increases confidence in the result,

and (ii) as one accounts for the uncertainty due to the variation in the modelling elements in the sample one buffers against changes in the modelling elements including changes in the future that may not be foreseen at this point in time. The reliability of the output result rests upon the consideration that the larger the sample of models under consideration, then the richer is the output aggregate and the greater the confidence that one can have in the accuracy of the parameters, the completeness of the assumptions, the soundness of the choices embedded in the model and the output therefrom.

The uncertainty due to the variation in the modelling elements in the sample is not seen as a problem; on the contrary as the model is synthesized it is seen as a fortune in disguise. Such uncertainty reflects the variation in the consensus across the models of the different experts groups in the field and can be probed by appropriate sensitivity analysis to identify the major factors of disagreement. For this area, the STM project presents the largest most comprehensive platform of comparison between the major models in the field.

This project is dedicated to the generation and development of the STM and the subsequent analysis of the results. The key outputs of the STM were compared under the criterion of sustainability from both energy and environmental perspectives. Advantage was taken of the sensitivity analysis to estimate the correlations between the STM outputs and set up an analytical simulation to measure the stochastic change in the sustainability measures (e.g. GHG emissions) relative to the reference system (generally the conventional system) for various future scenarios. The outcomes of the comparative analyses of the STM results have been aggregated into a proposed strategic framework for the planning of the future of passenger cars transport. In building the strategic framework this project was the first in our field of study to notice that the World needs a sustainable energy system rather than simply a sustainable transport system and therefore the synergistic behaviour between the transport and power sectors was investigated. This study identified strategies that maximize the global reduction in GHG emissions using alternative resources. In this respect the STM was designed to generate results in different forms including the normalized form, i.e. in MJ/MJ_W, to allow analysis across different sectors of fuel consumption. The results from this important outlook contributed in the shaping of the strategic framework. Finally the analyses of the STM results were taken further by placing the strategic framework into perspective in a UK based study of future scenarios. The developed framework

was used to propose a set of future scenarios and the effect of the progressive implementation of these scenarios against the business-as-usual forecast was scaled.

8.2 Conclusions

8.2.1 Sensitivity analysis results

In general, the WtW result of the options of vehicles driven by fossil fuels is predominated by the variability of the vehicle performances due to the combined effect of changes in the driving cycle, vehicle weight and time frame, and is relatively insignificantly sensitive to the fuel chain (WtT) stages. On the other hand, the WtT stages of the options of vehicles powered by non-fossil fuels (e.g. biomass) have generally better impact on the energy consumption output and large impact on the GHG emissions output. There are three findings from the sensitivity analysis that have important influence and help to explain the complexity of some options on which there is large controversy.

First, in the case of GHG emissions from cultivated biomass systems in excess of 80% of the variation is related to the stages of the fuel chain on which the CO_2 emissions from land use change and the N_2O emissions from fertilizers use have the largest impact. Secondly in the case of renewables based chains, the CO_2 emissions associated with the process (e.g. plant) construction were found to have a large impact on the overall CO_2 emissions on a WtW basis. In fact, in the case of the renewable electricity driven BEV chain the variation in the CO_2 emissions from the construction and operation of the renewable power plant/farm forms approximately 90% of the STM output variation. Therefore the standing of CO_2 emissions associated with the system construction is very much different when it comes to renewables based chains as compared to fossil fuels based chains where this type of emissions has insignificant impact on the overall profile. Thirdly, there is interestingly disagreement among the different expert groups in the field over the account of thermal losses in the nuclear power plant and this has a large impact on the measure of efficiency for the uranium based chains. The JEC model adopts the ‘efficiency method’ for the calculation of energy consumption where the efficiency of electricity generation from nuclear power is based on the heat released by nuclear fission and the thermal losses in the power plant are accounted in energy terms. On the contrary, given that uranium is not combustible and does not have a heating value it is treated by GREET as an auxiliary material, where only the energy associated with the material supply is considered. Clearly there

is a need for a standard to define what types of energy should be accounted in the measurement of efficiency. Although engineers differentiate between efficiencies based on HHV and LHV there is currently no standard which differentiates between efficiencies based on total energy and materials energy.

8.2.2 Comparative analysis results

The STM generates the one output which sums the richness of the information embedded in the major models in the field. It is contended that the results will provide informed answers to many energy policy questions that have been strongly debated including the viability of the hydrogen economy. In laying out the results of the comparative analysis examination of FCVs versus BEVs was made. It was found that in most of the options under study the all-electric cars were superior to fuel cell cars. The approach of comparison among the different options under study is very important; for example, the author did not repeat the mistake of looking at the apparent benefits of hydrogen relative to the conventional transport fuel whilst turning a blind eye on hydrogen's standing in terms of energy and environmental savings with respect to its rival alternatives.

The comparative analyses of the different options under study based on as complete portfolios as possible show that electrons are superior to hydrogen. First, hydrogen FCVs perform similarly or worse than BEVs. In the case of nuclear resourced options, hydrogen FCVs are a complete non-starter on an energy basis; also in the case of non-biomass renewables the electric options are significantly more energy efficient as compared to the hydrogen options implying greater substitution of, and hence less use of exhaustible resources such as fossil fuels in the transport sector. Nevertheless, hydrogen does outperform other options with regard to the option of cellulosic biomass resources especially with the implementation of CCS technology in the gasification plant. The implementation of CCS in the gasification plant forms a carbon sink and guarantees large CO_2 emissions savings. Secondly, while on one hand some time is required to resolve some issues concerning BEVs, such as the driving range and recharging time, there are also issues concerning hydrogen technologies such as storage and distribution infrastructure. Thus a minor role for hydrogen in the transport sector is envisaged with it being limited to the exploitation of cellulosic biomass such as waste wood (when this is feasible). Thus the creation of an energy economy based on hydrogen fuel is a highly questionable objective.

However, the short term penetration of BEVs in the transport sector will be detrimental if the electricity is coal based without the implementation of CCS technology. Thus the use of BEVs in transport in the short run is also tied to the development and implementation of feasible CCS technology. Nevertheless, BEVs can guarantee significant CO_2 emissions reductions with electricity from renewables, nuclear and even NG with high efficiency CCGT power plants. In fact the guaranteed savings are large (in excess of 100 g per 1 km) for renewables and nuclear driven BEVs.

In the case of biofuels the real limitation is land use which is believed to enforce a bell-shaped curve on the production of biofuels from cultivated biomass. In this sense the production of bio-hydrogen from waste wood (e.g. forest residue, furniture, etc) is the most attractive option as it is independent of land use and presents a second generation option that can be sustained in the long run and guarantees significant CO_2 emissions savings even without CCS technology. On the other hand, the sugar ethanol options with safe implementation including avoidance of CO_2 emissions from indirect land use change, the low use of nitrogen fertilizers and carbon balanced fermentation process guarantees significant CO_2 emissions savings and have a good potential for large CO_2 emissions savings. Also, from amongst the other types of cultivated biomass considered, the sugar ethanol options perform the best in terms of land use efficiency and can be used to make best use of available degraded, set aside and marginal land before the demand for bioethanol starts competing with the demand for food.

8.2.3 Cross sectoral analysis

In this part of the work synergies between the power and transport sectors were assessed to identify which strategies delay the global reduction in GHG emissions and which are to be preferred on from an overall perspective. It was found that the strategy in which the use of alternatives such as NG, nuclear and renewables is not diversified but fed only into the power sector allows one to (a) avoid the global increase in GHG emissions from indirect resource use change (iRUC) and make use of the conventional power resources displaced from the power sector to maximize the global reduction in GHG emissions, and (b) isolate the power market to maintain the upstream energy security.

8.2.4 Framework analysis

The study of the framework that resulted from the concepts implied by the STM and the subsequent analyses under different scenarios was considered in this part of the work. The aim was to put outcomes into perspective in a more specific context and address the important question of whether it is still possible to save the World from the disastrous consequences of Global Warming. It was found that the implementation of a scenario with a complete technology package including nuclear, renewables and CCS may result in zero GHG emissions in the power sector by 2050 and the same in the passenger cars transport subsector by 2060. Therefore the realisation of a target equivalent to the 350 ppm CO_2 atmospheric concentration target, which was posed by James Hansen and his colleagues in 2008 (Hansen *et al.*, 2008), is not impossible. However the different alternatives presented work synergistically, and their optimum strength come with the complete technology package. It was shown that the absence of any of the major technologies such as renewables, nuclear or CCS will significantly affect the performance of the overall scenario.

References

(S&T)^2 CONSULTANTS INC. 2009. GHGenius model software. Version 3.15 ed. Canada. Available: http://www.ghgenius.ca/downloads.php#top.

ACCUREX 1996. *Evaluation of Fuel-Cycle Emissions on a Reactivity Basis*. Volume 1. Accurex Environmental Corporation, prepared for California Air Resources Board. Mountain View, California.

ADL 1996. *Integrated Fuel Chain Analysis Model (IFCAM)*. Report to Ford Motor Company. Arthur D. Little. Cambridge, Massachusetts.

AHLVIK, P. 2008. *Well to wheel efficiency for heavy duty vehicles - Comparison of various biofuels in a long distance lorry and a city bus*. Publikation 2001:85. Ecotraffic AB, Swedish National Road Administration. Stockholm, Sweden.

AHMAN, M. 2000. Primary energy efficiency of alternative powertrain in vehicles. *Energy*, 26**,** 973-989.

ANDRESS, D. 1998. *Comparison of Ethanol Fuel Cycles in the GHG Models developed by Michael Wang and Mark Delucchi*. David Andress & Associates Inc., prepared for DOE, Office of Fuel Development and Office of Transportation Technologies, Energy Efficiency and Renewable Energy under contract DE-AC05-96OR22464. Kensington, Maryland.

ANL 2009. Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET). *In:* WANG, M. (ed.) Version 1.8c0 ed. Argonne, Illinois. Available: http://greet.es.anl.gov/main.

ATTARAN, M. 1992. *MSIS - Management Science Information Systems*, New York, John Wiley & Sons.

BAER, P., ATHANASIOU, T. & KARTHA, S. 2009. *A 350 ppm Emergency Pathway*. The Greenhouse Development Rights project of EcoEquity and the Stockholm Environment Institute (SEI). California / Stockholm. Available: http://gdrights.org/wp-content/uploads/2009/11/a-350-ppm-emergency-pathway-v2.pdf [Accessed October 2010].

BANISTER, D., STEAD, D., STEEN, P., AKERMAN, J., DREBORG, K., NIJKAMP, P. & SCHLEICHER-TAPPESER, R. 2000. *European Transport Policy and Sustainable Mobility*, London, E & FN Spon. ISBN 0-415-231892

BENTLEY, J. 1992. *The Impact of Electric Vehicles on CO_2 emissions*. Arthur D. Little Inc. Cambridge, Massachusetts.

BENTLY, R. W. 2002. Global oil & gas depletion: an overview. *Energy Policy*, 30**,** 189-205.

BINDER, M., FALTENBACHER, M. & FISCHER, M. 2005. Hydrogen as Fuel for Urban Transportation Environmental Footprint of Different Hydrogen Production Routes and the Influence on the Total Life Cycle of FC Powered Transportation Systems: An LCA Case Study within CUTE. *In:* PAPASAVVA, S., FTHENAKIS, V. , ed. Materials Research Society Fall Meeting, 2005 Boston, MA.

BISHOP, N. & WATSON, M. 2004. *Future Road Fuels*. Petroleum Industry Association Limited (UKPIA). London. Available: http://www.ukpia.com/files/pdf/ukpia-future-road-fuels.pdf [Accessed October 2010].

BÖRJESSON, P. 2009. Good or bad bioethanol from a greenhouse gas perspective – what determines this? *Applied Energy*, 86**,** 589–594.

BOSSEL, U. 2005. *Does a hydrogen economy make sense?* European Fuel Cell Forum. Oberrohrdorf, Switzerland. Available: http://images.pluginamerica.org/Bossel_E13.pdf [Accessed October 2010].

BOSSEL, U., ELIASSON, B. & TAYLOR, G. 2003. *The Future of the Hydrogen Economy: Bright or Bleak?* Final Report. European Fuel Cell Forum. Oberrohrdorf, Switzerland. Available: www.iceland.de/fileadmin/template/iceland/efcf.pdf [Accessed October 2010].

BOWERS, H. I., FULLER, L. C. & MYERS, M. L. 1987. *Cost Estimating Relationships for Nuclear Power Plant Operation and Maintenance*. ORNL/TM-10563. Oak Ridge National Laboratory. Oak Ridge, TN.

BROGAN, J. & VENKATESWARAN, S. 1992. Diverse Choices for Electric and Hybrid Motor Vehicles: Implications for National Planners. *Urban Electric Vehicle Conference.* Stockholm, Sweden.

CAI, Z., LAUGHLIN, R. J. & STEVENS, R. J. 2001. Nitrous oxide and dinitrogen emissions fromsoil under different water regimes and straw amendment. *Chemosphere,* 42**,** 113–21.

CHERUBINI, F. 2010. GHG balances of bioenergy systems - Overview of key steps in the production chain and methodological concerns. *Renewable Energy,* 35**,** 1565-1573.

CHERUBINI, F., BIRD, N. D., COWIE, A., JUNGMEIER, G., SCHLAMADINGER, B. & WOESS-GALLASCH, S. 2009. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, Conservation and Recycling,* 53**,** 434–447.

CLEANER VEHICLES TASK FORCE (CVTF) 2000. *The Report of the Alternative Fuels Group of the Cleaner Vehicles Task Force - An assessment of the Emissions Performance of Alternative and Conventional Fuels*. URN: 00/660. DTI Automotive Directorate. TSO: London.

CONANT, R., PAUSTIAN, K. & ELLIOT, E. T. 2001. Grassland management and conversion into grassland: effects on soil carbon. *Ecological Applications,* 11**,** 343–55.

CONTADINI, J. F. 2002. *Life cycle assessment of fuel cell vehicles - Dealing with uncertainties.* Ph.D. Thesis, University of California, Davis.

CONVERSE, A. 2006. The impact of large-scale energy storage requirements on the choice between electricity and hydrogen as the major energy carrier in a non-fossil renewables-only scenario. *Energy Policy,* 34**,** 3374-3376

DARROW, K. G. 1994a. *Comparison of Fuel-Cycle Emissions for Electric Vehicle and Ultra-Low Emissions Natural Gas Vehicle*. Energy International Inc., prepared for Southern California Gas Company. Bellevue, Washington.

DARROW, K. G. 1994b. *Light-Duty Vehicle Fuel-Cycle Emissions Analysis*. Energy International Inc., prepared for Gas Research Institute. Bellevue, Washington.

DECC 2010a. *2008 final UK greenhouse gas emissions*. Data tables (Files type: .xls). Department of Energy and Climate Change. London. Available: http://www.decc.gov.uk/assets/decc/Statistics/climate_change/362-uk-greenhouse-gas-emissions.xls [Accessed October 2010].

DECC 2010b. *Digest of United Kingdom energy statistics (DUKES)*. *In:* MACLEAY, I., HARRIS, K., ANNUT, A. (ed.) Department of Energy & Climate Change. TSO: London. Available: http://www.decc.gov.uk/en/content/cms/statistics/publications/dukes/.

DELUCCHI, M. 1991. *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*. Volume 1, Main text. ANL/ESD/TM-22. Center for Transportation Research, Energy Systems Division, Argonne National Laboratory. Argonne, Illinois.

DELUCCHI, M. 1993. *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*. Volume 2, Appendices A-S. ANL/ESD/TM-22. Center for Transportation Research, Energy Systems Division, Argonne National Laboratory. Argonne, Illinois.

DELUCCHI, M. 1997. *A Revised Model of Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity Institute of Transport Studies*. UCD-ITS-RR-97-22. University of California, Davis. California.

DELUCCHI, M. 2003. *A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating & Cooking Fuels, and Materials - Documentation of Methods and Data*. Main Report. UCD-ITS-RR-03-17. University of California, Institute of Transport Studies. Davis, California.

DELUCCHI, M. 2005. *A Multi-Country Analysis of Lifecycle Emissions from Transportation Fuels and Motor Vehicles*. UCD-ITS-RR-05-10. University of California, Institute of Transportation Studies, prepared for Nissan Motor Company. Davis, California. Available: www.its.ucdavis.edu/publications/2005/UCD-ITS-RR-05-10.pdf [Accessed October 2010].

DEMIRBAS, A. 2002. Pyrolysis and steam gasification processes of black liquor. *Energy Conversion and Management* 43**,** 877–884.

DFT 2009. *Transport Trends*. Section 1, Data tables (File: section1rvc.xls). Department for Transport. London. Available: www.dft.gov.uk/pgr/statistics/datatablespublications/trends/current/section1rvc.xls [Accessed October 2010].

DOHERTY, G. 1994. *Developing Quality Systems in Education*, London, Taylor & Francis.

DOW JONES NEWSWIRES (DJ). 2007. Global Food Demand to Double by 2050. *FLEXNEWS* [Online]. Available: www.flex-news-food.com [Accessed April 2010].

E4TECH, ELEMENT ENERGY & EOIN LEES ENERGY 2004. *A strategic framework for hydrogen energy in the UK*. Final Report. URN 04/2040. Department of Business Innovation & Skills (BIS), formely the Department of Trade & Industry (DTI). London. Available: http://www.berr.gov.uk/files/file26737.pdf [Accessed October 2010].

ECKERMANN, E. 2001. *World history of the automobile*, Pennsylvania, SAE Publications Group.

ECOTRAFFIC AB 1992. *Motor Fuels from Sources to Final Use*. Final Report on an Energy and Emissions System Study. Swedish National Road Administration. Stockholm, Sweden.

EDWARDS, P., KUZNETSOV, V., DAVID, W. & BRANDON, N. 2008. Hydrogen and fuel cells: Towards a sustainable energy future. *Energy Policy*, 36**,** 4356-4362.

EDWARDS, R., GRIESEMANN, J. C., LARIVÉ, J. F. & MAHIEU, V. 2007. *Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*. Version 2c. Main Report. European Commission, Institute for Environment and Sustainability. Ispra, Italy. Available: http://ies.jrc.ec.europa.eu/jec-research-collaboration/downloads-jec.html [Accessed October 2010].

ELSAYED, M. A., MATTHEWS, R. & MORTIMER, N. D. 2003. *Carbon and Energy Balances for a Range of Biofuels Options*. Project No. B/B6/00784/REP URN 03/836. Sheffield Hallam University, Resources Research Unit. Sheffield.

EPA 1995. *Compilation of Air Pollutant Emission Factors AP-42*. Fifth Edition. Volume I: Stationary Point and Area Sources. U.S. Environmental Protection Department. Research Triangle Park, NC.

EREC 2004. *Renewable Energy Scenario to 2040*. European Renewable Energy Council, Renewable Energy House. Brussels. Available: http://www.erec.org/fileadmin/erec_docs/Documents/Publications/EREC_Scenario_2040.pdf [Accessed October 2010].

ESRL-NOAA 5 November 2010. *Atmospheric CO2 for October 2010*. Earth Systems Research Laboratory (ESRL) / National Oceanic and Atmospheric Administration (NOAA). Mauna Loa Observatory, Hawaii. Available: http://co2now.org/ [Accessed October 2010].

EUROPEN 1999. *Use of Life Cycle Assessment (LCA) as a Policy Tool in the Field of Sustainable Packaging Waste Management*. The European Organization for Packaging and the Environment. Brussels, Belgium. Available: www.europen.be/download_protected_file.php?file=48 [Accessed October 2010].

EWING, J. 2010. Electric Cars Moving From Prototype to Showroom. *The New York Times* [Online]. Available: http://www.nytimes.com/2010/03/01/business/global/01autoshow.html?_r=1 [Accessed October 2010].

EYRE, N. & MICHAELIS, L. 1991. *The Impact of UK Electricity, Gas and Oil Use on Global Warming*. AEA-EE-0211. AEA Technology plc. London.

FAGUENDES DE ALMEIDA, E. & BOMTEMPO, J. V. 2007. *The Performance of the Brazilian Biofuels: An Economic, Environmental and Social Analysis*. Discussion Paper. 2007-5. Joint Transport Research Centre, Federal University of Rio de Janeiro. Rio de Janeiro. Available: http://www.internationaltransportforum.org/jtrc/DiscussionPapers/DiscussionPaper5.pdf [Accessed October 2010].

FARGIONE, J., HILL, J., TILMAN, D., POLASKY, S. & HAWTHORNE, P. 2008. Land clearing and the biofuel carbon debt. *Science,* 319**,** 1235–1238.

FARRELL, A. E. & SPERLING, D. 2007. *A Low-Carbon Fuel Standard for California*. Parts 1 & 2. University of California. California. Available: http://www.energy.ca.gov/low_carbon_fuel_standard/UC_LCFS_study_Part_1-FINAL.pdf; http://www.energy.ca.gov/low_carbon_fuel_standard/UC_LCFS_study_Part_2-FINAL.pdf [Accessed October 2010].

FRANCK, A., BERDAHL, J. D., HANSON, J. D., LIEBIG, M. A. & JOHNSON, H. A. 2004. Biomass and carbon partitioning in switchgrass. *CROP SCIENCE,* 44**,** 1391–6.

FREEDMAN, D., PISANI, R. & PURVES, R. 1997. *Statistics,* New York, U.S., W.W. Norton & Company.

FRITSCHE, U. R. 2001. *Introducing the GEMIS software family*. Öko-Institut (Institute for Applied Ecology) Darmstadt, Germany. Available: http://www.oeko.de/service/gemis/files/info/g4_info_en.pdf [Accessed October 2010].

FRITSCHE, U. R. 2008. *Bioenergy Life-Cycle Analysis: Beyond Biofuels*. ETC/ACC Technical Paper 2008/18. The European Topic Centre on Air and Climate Change (ETC/ACC). Bilthoven, Netherlands. Available: http://air-climate.eionet.europa.eu/docs/ETCACC_TP_2008_7_LCA_bioenergy.pdf [Accessed October 2010].

FRITSCHE, U. R. 2010. *The "iLUC Factor" as a Means to Hedge Risks of GHG Emissions from Indirect Land Use Change*. Working Paper. Energy & Climate Division, Oeko-Institut. Darmstadt. Available: www.oeko.de/oekodoc/1030/2010-082-en.pdf [Accessed October 2010].

FTHENAKIS, V. & KIM, H. C. 2007. Greenhouse-gas emissions from solar electric- and nuclear power: A life-cycle study. *Energy Policy,* 35**,** 2549–2557.

GABRIELLE, B. & GAGNAIRE, N. 2008. Life-cycle assessment of straw use in bioethanol production: a case study based on biophysical modelling. *Biomass Bioenergy,* 32**,** 431–41.

GARTEN, C. & WULLSCHLEGER, S. D. 2000. Soil carbon dynamics beneath switchgrass as indicated by stable isotope analysis. *Journal of Environmental Quality,* 29**,** 645–53.
GEBHART, D., JOHNSON, H. B., MAYEUX, H. S. & POLLEY, H. W. 1994. The CRP increases soil organic carbon. *Journal of Soil and Water Conservation,* 49**,** 488–92.
GEERKEN, T., LASSAUX, S., RENZONI, R. & TIMMERMANS, V. 2004. *Review of hydrogen LCAs for the Hysociety project*. Final report. 2004/IMS/R/228. Flemish Institute for Technological Research / University of Liège, study commissioned by the Hysociety project (EU, 5th Framework Program). Belgium.
GM, ARGONNE NATIONAL LABORATORY & AIR IMPROVEMENT RESOURCE INC. 2005. *Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems — A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions*. Argonne National Laboratory (ANL). Argonne, Illinois. Available: http://www.transportation.anl.gov/pdfs/TA/339.pdf [Accessed October 2010].
GM, ARGONNE NATIONAL LABORATORY, BP, EXXONMOBIL & SHELL 2001. *Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems — North American Analysis*. Volume 1-2. Argonne National Laboratory. Argonne, Illinois.
GM, L-B-SYSTEMTECHNIK, BP, EXXONMOBIL & TOTALFINAELF 2002a. *ANNEX - Methodology, Assumptions, Descriptions, Calculations, Results- to the GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - A European Study*. Full Background Report. L-B-Systemtechnik. Ottobrunn, Germany. Available: www.lbst.de/.../studies.../Annex_Full_Background_Report_27092002.pdf [Accessed October 2010].
GM, L-B-SYSTEMTECHNIK, BP, EXXONMOBIL & TOTALFINAELF 2002b. *GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - A European Study*. Report. L-B-Systemtechnik. Ottobrunn, Germany. Available: http://www.lbst.de/publications/studies__d/2002/TheReport_Euro-WTW_27092002.pdf [Accessed October 2010].
GNANSOUNOU, E., DAURIAT, A., VILLEGAS, J. & PANICHELLI, L. 2009. Life cycle assessment of biofuels: Energy and greenhouse gas balances. *Bioresource Technology,* 100**,** 4919–4930.
GNANSOUNOU, E., PANICHELLI, L., DAURIAT, A. & VILLEGAS, J. 2008. *Accounting for indirect land-use changes in GHG balances of biofuels - Review of current approaches*. Working Paper. École Polytechnique Fédérale de Lausanne. Lausanne. Available: http://infoscience.epfl.ch/record/121496/files/Accounting_for_ILUC_in_biofuels_production.pdf [Accessed October 2010].
GOLDEMBERG, J. 2000. *World Energy Assessment: Energy and the Challenge of Sustainability,* New York, United Nations Development Program (UNDP).
GOVER, M., COLLINGS, S., HITCHCOCK, G., MOON, D. & WILKINS, G. 1996. *Alternative Road Transport Fuels: A Preliminary Life-cycle Study for the UK*. Volume 2. Energy Technology Support Unit (ETSU), AEA Technology plc. Harwell, Didcot, Oxfordshire.
GRAY, L. 2010. Biofuels cause four times more carbon emissions. *The Telegraph* [Online]. Available: http://www.telegraph.co.uk/earth/environment/climatechange/7614934/Biofuels-cause-four-times-more-carbon-emissions.html [Accessed October 2010].
HACKNEY, J. 1997. *Alternative fuel vehicle policy: A life cycle analysis tool for emissions, costs and energy efficiency with an application to the United States.* Master of Science, Technology and Policy Program, MIT.

HACKNEY, J. & NEUFVILLE, R. 2001. Life cycle model of alternative fuel vehicles: emissions, energy, and cost trade-offs. *Transportation Research Part A,* 35**,** 243-266.
HAMELINCK, C., KOOP, K., CROEZEN, H., KOPER, M., KAMPMAN, B. & BERGSMA, G. 2008. *Technical specification: greenhouse gas calculator for biofuel*. Version 2.1b. Report GAVE-08-01. The Netherlands Agency for Sustainability and Innovation (SenterNovem). Utrecht, Netherlands. Available: http://www.senternovem.nl/mmfiles/Technical%20specification%20v2.1b%20-%202008%2008%2013_final_tcm24-327320.pdf [Accessed October 2010].
HANSEN, J., SATO, M., KHARECHA, P., BEERLING, D., BERNER, R., MASSON-DELMOTTE, V., PAGANI, M., RAYMO, M., ROYER, D. L. & ZACHOS, J. C. 2008. Target Atmospheric CO2: Where Should Humanity Aim? *The Open Atmospheric Science Journal,* 2**,** 217-231.
HEKKERT, M., HENDRIKS, F., FAAIJ, A. & NEELIS, M. 2005. Natural gas as an alternative to crude oil in automotive fuel chains well-to-wheel analysis and transition strategy development. *Energy Policy,* 33**,** 579-594.
HELLER, M., KEOLEIAN, G. A. & VOLK, T. A. 2003. Life cycle assessment of a willow bioenergy cropping system. *Biomass Bioenergy,* 25**,** 147–65.
HELTON, J. & DAVIS, F. J. 2002. *Latin Hypercube Sampling and the Propagation of Uncertainty in Analyses of Complex Systems*. Sandia National Laboratories. California, U.S. Available: http://reference.kfupm.edu.sa/content/h/y/hypercube_sampling_and_the_propagation_o_87543.pdf [Accessed October 2010].
HICKMAN, R. & BANISTER, D. 2007. Looking over the horizon: Transport and reduced CO_2 emissions in the UK by 2030. *Transport Policy,* 14**,** 377-387.
HONG, B. & SLATICK, E. 1994. *Carbon Dioxide Emission Factors for Coal*. Quarterly Coal Report. Energy Information Administration (EIA). Washington, DC. Available: http://www.eia.doe.gov/cneaf/coal/quarterly/co2_article/co2.html [Accessed October 2010].
HUBBERT, M. K. 1956. *Nuclear energy and the fossil fuels*. Publication No. 95. Shell Development Company. Houston, Texas. Available: http://www.oilcrisis.com/hubbert/1956/1956.pdf [Accessed October 2010].
HUSSAIN, M., DINCER, I. & LI, X. 2007. A preliminary life cycle assessment of PEM fuel cell powered automobiles. *Applied Thermal Engineering,* 27**,** 2294-2299.
IEA 1999. *Automotive fuels for the future - the search for alternatives*. Automotive Fuels Information Service (AFIS), International Energy Agency. IEA/AFIS: Paris. Available: www.iea.org/textbase/nppdf/free/1990/autofuel99.pdf [Accessed October 2010].
IMF 2008. *World Economic Outlook Update - Global slowdown and rising inflation*. International Monetary Fund. Washington, DC. Available: http://www.imf.org/external/pubs/ft/weo/2008/update/02/index.htm [Accessed October 2010].
INDUSTRY TASKFORCE ON PEAK OIL & ENERGY SECURITY (ITPOES) 2010. *The Oil Crunch - A wake-up call for the UK economy. In:* ROBERTS, S. (ed.) 2nd Report. ITPOES. OVE ARUP & PARTNERS LTD: London. Available: http://peakoiltaskforce.net/download-the-report/2010-peak-oil-report/ [Accessed October 2010].
INTERNATIONAL STANDARD ISO 14041 1998. *Environmental Management – Life cycle assessment – Goal and Scope Definition and Inventory Analysis*. First edition. International Organization for Standardization. Geneva, Switzerland.

IPCC 1996. *Climate Change 1995: The Science of Climate Change*. Contribution of Working Group I to the Second Assessment Report of the IPCC Intergovernmental Panel on Climate Change. CAMBRIDGE UNIVERSITY PRESS: Cambridge, MA.

IPCC 2006. *IPCC Guidelines for National Greenhouse Gas Inventories - Agriculture, Forestry and Other Land Use*. *In:* EGGLESTON, H. S., BUENDIA, L., MIWA, K., NGARA, T., TANABE, K. (ed.) Volume 4. Institute for Global Environmental Strategies (IGES). Hayama, Japan. Available: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html [Accessed October 2010].

JACQUES, J., LAVERGNE, C. & DEVICTOR, N. 2006. Sensitivity analysis in presence of model uncertainty and correlated inputs. *Reliability Engineering and System Safety*, 91**,** 1126–1134.

JOHANSSON, B., MCCORMICK, K., NEIJ, L. & TURKENBURG, W. The Potentials of Renewable Energy - Thematic Background Paper. *In:* International Conference for Renewable Energies, 2004 Bonn.

JRC, EUCAR & CONCAWE 2008a. *Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*. Version 3. WTT Appendix 4 (.xls). European Commission, Institute for Environment and Sustainability. Ispra, Italy. Available: http://ies.jrc.ec.europa.eu/jec-research-collaboration/downloads-jec.html [Accessed October 2010].

JRC, EUCAR & CONCAWE 2008b. *Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*. Version 3. WTT Appendix 2 (.pdf). European Commission, Institute for Environment and Sustainability. Ispra, Italy. Available: http://ies.jrc.ec.europa.eu/uploads/media/WTT%20App%202%20v30%20181108.pdf [Accessed October 2010].

JRC, EUCAR & CONCAWE 2008c. *Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*. Version 3. TTW Report. European Commission, Institute for Environment and Sustainability. Ispra, Italy. Available: http://ies.jrc.ec.europa.eu/uploads/media/V3.1%20TTW%20Report%2007102008.pdf [Accessed October 2010].

KALTSCHMITT, M. & HARTMANN, H. 2001. *Energie aus Biomasse - Grundlagen, Techniken und Verfahren*, Heidelberg, Springer Verlag. ISBN 3-540-64853-4

KEVIN, H. 2006. Department of Energy Handing Out Hydrogen Research Funds. *HydrogenCarsNow.com* [Online]. Available: http://www.hydrogencarsnow.com/blog2/index.php/news/department-of-energy-handing-out-hydrogen-research-funds/ [Accessed October 2010].

KORONEOS, C., DOMPROS, A., ROUMBAS, G. & MOUSSIOPOULOS, N. 2004. Life cycle assessment of hydrogen fuel production processes. *International Journal of Hydrogen Energy* 29**,** 1443-1450.

LAL, R. 2008. Promise and limitations of soils to minimize climate change. *Journal of Soil Water Conservation*, 63**,** 113–8.

LAL, R., KIMBLE, L. M., FOLLET, R. F. & COLE, C. V. 1999. *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect*, Florida, CRC Press LLC. 1-57504-112-X

LANE, B. 2006. *Life Cycle Assessment of Vehicle Fuels and Technologies*. Ecolane Transport Consultancy. London.

LARIVÉ, J. F. 2009. *JRC/EUCAR/CONCAWE WTW Analysis of European Road Fuels - A European Perspective on fuels LCA Modelling*. PowerPoints. Conservation of Clean Air and Water in Europe (Concawe). Brussels, Belgium. Available:

http://www.crcao.com/workshops/LCA%20October%202009/Session%202/3-Larive,%20Jean-Francois.pdf [Accessed October 2010].
LARSON, E. A review of LCA studies on liquid biofuels for the transport sector. *In:* Scientific and Technical Advisory Panel (STAP) workshop on liquid biofuels, 29 August to 1 September 2005 New Delhi, India.
LBST 2008. *E3database - An Introduction into the Life-Cycle Analysis Calculation Tool*. Ludwig-Bölkow-Systemtechnik GmbH. Ottobrunn, Germany.
LÓPEZ, J., GÓMEZ, A., APARICIO, F. & SÁNCHEZ, F. 2009. Comparison of GHG emissions from diesel, biodiesel and natural gas refuse trucks of the City of Madrid. *Applied Energy,* 86**,** 610–615.
MACEDO, I. 2004. *Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil.* Government of the State of São Paulo. São Paulo, Brazil.
MACKAY, D. 2009a. Could the Sahara's sun save us? *The Sunday Times* [Online]. Available: http://business.timesonline.co.uk/tol/business/industry_sectors/natural_resources/article6446064.ece [Accessed October 2010].
MACKAY, D. 2009b. *SUSTAINABLE ENERGY - WITHOUT THE HOT AIR*, Cambridge, UIT Cambridge. ISBN 978-0-9544529-3-3
MACLEAN, H. & LAVE, L. 2003a. Evaluating automobile fuel/propulsion system technologies. *Progress in Energy and Combustion Science,* 29**,** 1–69.
MACLEAN, H. & LAVE, L. 2003b. Life Cycle Assessment of Automobile/Fuel Options. *Environ. Sci. Technol.,* 37 5445-5452.
MANN, M. & SPATH, P. 1997. *Life Cycle Assessment of a Biomass Gasification Combined-Cycle Power System*. Technical Report. NREL/TP-430-23076. National Renewable Energy Laboratory. Golden, Colorado.
MATHEWS, J. & TAN, H. 2009. Biofuels and indirect land use change effects: the debate continues. *Biofuels, Bioprod. Bioref.* DOI: 10.1002/bbb.147
MCKAY, M. D., BECKMAN, R. J. & CONOVER, W. J. 1979. A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics,* 21**,** 239-245.
MOOD, A., GRAYBILL, F. & BOES, D. 1974. *Introduction to the theory of statistics,* Singapore, McGraw Hill.
MORGAN, B. 1999. *Elements of Simulation,* Florida, U.S., CRC.
NREL 1991. *A Comparative Analysis of the Environmental Outputs of Future Biomass-Ethanol production Cycles and Crude Oil/Reformulated Gasoline Production Cycles, Appendices*. National Renewable Energy Laboratory, prepared for the US Department of Energy, Office of Transportation Technologies and Office of Planning and Assessment. Golden, Colorado.
NREL 1992. *Fuel Cycle Evaluations of Biomass-Ethanol and Reformulated Gasoline*. National Renewable Energy Laboratory, prepared for the US Department of Energy, Office of Transportation Technologies and Office of Planning and Assessment. Golden, Colorado.
ÖKO-INSTITUT 2008. Global Emissions Model for Integrated Systems (GEMIS). *In:* FRITSCHE, U. R. (ed.) Version 4.5 ed. Darmstadt, Germany. Available: http://www.oeko.de/service/gemis/en/material.htm.
ORNL 2003. *Bioenergy Conversion Factors*. Oak Ridge National Laboratory. Oak Ridge, TN. Available: http://bioenergy.ornl.gov/papers/misc/energy_conv.html [Accessed October 2010].
PALISADE 2010a. @Risk: Risk Analysis Software. Version 5.7 ed. NY. Available: http://www.palisade.com/.

PALISADE 2010b. StatTools: Statistics Software. Version 5.7 ed. NY. Available: http://www.palisade.com/.

PEÑA, N. 2008. *Biofuels for Transportation: A Climate Perspective*. Solutions White Paper Series. Pew Center on Global Climate Change. Arlington, VA. Available: http://www.pewclimate.org/docUploads/BiofuelsFINAL.pdf [Accessed October 2010].

PRIDMORE, A. & BRISTOW, A. L. 2002. *The role of hydrogen in powering road transport*. Tyndall Working Paper No. 19. Tyndall Centre for Climate Change Research. Norwich, UK. Available: http://www.tyndall.ac.uk/sites/default/files/wp19.pdf [Accessed October 2010].

PUNTER, G., RICKEARD, D., LARIVÉ, J.-F., EDWARDS, R., MORTIMER, N., HORNE, R., BAUEN, A. & WOODS, J. 2004. *Well-to-Wheel Evaluation for Production of Ethanol from Wheat*. A Report by the LowCVP Fuels Working Group, WTW Sub-Group. FWG-P-04-024. LowCVP. London. Available: http://www.rms.lv/bionett/Files/BioE-2004-001%20Ethanol_WTW_final_report.pdf [Accessed October 2010].

REPORTER. 2010. Paris Motor Show: Small Hybrids for Global Markets. *hybridCARS.com* [Online]. Available: http://www.hybridcars.com/news/paris-motor-show-small-hybrids-global-markets-28652.html [Accessed October 2010].

ROTTY, R. M., PERRY, A. M. & REISTER, D. B. 1975. *Net Energy from Nuclear Power*. IEA-75-3. Institute for Energy Analysis, Oak Ridge Associated Universities. Oak Ridge, TN. Available: www.stormsmith.nl/report20071013/partC.pdf [Accessed October 2010].

RUMSEY, D. 2007. *Intermediate Statistics*, Indiana, U.S., Wiley Publishing.

SALTELLI, A., CHAN, K. & SCOTT, E. M. 2000. *Sensitivity analysis*, New York, John Wiley & Sons.

SCHWIEGER, V. Variance-based Sensitivity Analysis for Model Evaluation in Engineering Surveys. *In:* The 3rd International Conference on Engineering Surveying (INGEO 2004), November 11-13, 2004 Bratislava, Slovakia.

SEARCHINGER, T., HEIMLICH, R., HOUGHTON, R. A., DONG, F., ELOBEID, A., FABIOSA, J., TOKGOZ, S., HAYES, D. & YU, T. 2008. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science*, 319**,** 1238-1240.

SI 2001. *Energy Needs, Choices, and Possibilities - Scenarios to 2050*. Global Business Environment, Shell International Limited. London. Available: www.cleanenergystates.org/CaseStudies/Shell_2050.pdf [Accessed October 2010].

SOBOL, I. M. 1993. Sensitivity estimates for nonlinear mathematical models. *Mathematical Modeling & Computational Experiment (Engl. Transl.)*, 1**,** 407–414.

SPATH, P. & MANN, M. 2001. *Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming*. Technical Report. NREL/TP-570-27637. National Renewable Energy Laboratory. Golden, Colorado.

SPATH, P. & MANN, M. 2004. *Life Cycle Assessment of Renewable Hydrogen Production via Wind/Electrolysis*. Milestone Report. NREL/MP-560-35404. National Renewable Energy Laboratory. Golden, Colorado.

SUBRAMANYAN, K., WU, Y., DIWEKAR, U. M. & WANG, M. 2008. New Stochastic Simulation Capability Applied to the GREET Model. *International Journal of Life Cycle Assessment*, 13**,** 278–285.

THE ASSOCIATED PRESS (AP). 2008. U.N.: 50 percent more food needed by 2030. *msnbc.com* [Online]. Available: http://www.msnbc.msn.com/id/24942035/ns/world_news-world_environment [Accessed October 2010].

THE AUTOMOTIVE EDITORS. 2010. The Top 14 Electric Cars from the Paris Motor Show. *Popular Mechanics* [Online]. Available: http://www.popularmechanics.com/cars/alternative-fuel/electric/electric-cars-at-paris-motor-show [Accessed October 2010].

TURNER, B., PLEVIN, R. J., O'HARE, M. & FARRELL, A. E. 2007. *Creating Markets for Green Biofuels: Measuring and improving environmental performance*. UCB-ITS-TSRC-RR-2007-1. UC Berkeley Transportation Sustainability Research Center, Institute of Transportation Studies, UC Berkeley. Berkeley, California. Available: http://escholarship.org/uc/item/0mm0m9xm.pdf [Accessed October 2010].

UNITED NATIONS GENERAL ASSEMBLY (UNGA) 1987. *Report of the World Commission on Environment and Development: Our Common Future*. Transmitted to the General Assembly as an Annex to document A/42/427 - Development and International Co-operation: Environment. UN: Oslo. Available: http://www.un-documents.net/ocf-cf.htm [Accessed October 2010].

UNNASCH, S. & PONT, J. 2007. *Full Fuel Cycle Assessment Well to Tank Energy Inputs, Emissions, and Water Impacts*. CEC-600-2007-002-D. TIAX LLC, prepared for California Energy Commission. Cupertino, California.

UTLU, Z. & HEPBASLI, A. 2003. A study on the evaluation of energy utilization efficiency in the Turkish residential-commercial sector using energy and exergy analyses. *Energy and Buildings*, 35**,** 1145-1153.

UTLU, Z. & HEPBASLI, A. 2007. A review on analyzing and evaluating the energy utilization efficiency of countries. *Renewable and Sustainable Energy Reviews*, 11**,** 1–29.

WANG, M. 1996. *GREET 1.0 - Transportation Fuel Cycles Models: Methodology and Use*. ANL/ESD-33. Center for Transportation Research, Argonne National Laboratory. Argonne, Illinois. Available: http://www.transportation.anl.gov/pdfs/TA/500.pdf [Accessed October 2010].

WANG, M. 1998. *Fuel-Cycle Greenhouse Gas Emissions Impacts of Alternative Transportation Fuels and Advanced Vehicle Technologies*. Center for Transportation Research, Argonne National Laboratory. Argonne, Illinois. Available: www.osti.gov/bridge/servlets/purl/11181-JK7bZw/webviewable/11181.pdf [Accessed October 2010].

WANG, M. 1999. *GREET 1.5 - Transportation Fuel-Cycle Model - Volume 1: Methodology, Development, Use & Results*. ANL-ESD-39. Center for Transportation Research, Argonne National Laboratory. Argonne, Illinois. Available: http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=14775 [Accessed October 2010].

WANG, M. 2001. *Development of GREET 1.6 Fuel Cycle Model for Transportation Fuels and Vehicle Technologies*. Final Report. ANL/ESD/TM-163. Center for Transportation Research, Argonne National Laboratory. Argonne, Illinois. Available: http://ntl.bts.gov/lib/14000/14900/14963/DE2002797947.pdf [Accessed October 2010].

WANG, M. & HAQ, Z. 2008. Response to February 7, 2008 Sciencexpress Article. Available: http://www.bioenergywiki.net/images/2/2c/Wang_response_to_land_use.pdf [Accessed October 2010].

WANG, M. & SANTINI, D. 1993. Magnitude and Value of Electric Vehicle Emissions Reductions for Six Driving Cycles in Four US Cities with Varying Air Quality Problems. *Transportation Research Record,* 1416**,** 33-42.

WANG, M., WU, Y. & ELGOWAINY, A. 2005. *Operating Manual for GREET: Version 1.7*. ANL/ESD/05-3. Center for Transportation Research, Argonne National Laboratory. Argonne, Illinois.

WARNER, E. S. 2009. *Evaluating Life Cycle Assessment (LCA) Models for use in a Low Carbon Fuel Standard Policy.* Master of Science, The University of Minnesota.

WCI 2005. *The Coal Resource: A Comprehensive Overview of Coal*. World Coal Institute, World Coal Association. London. Available: http://www.worldcoal.org/bin/pdf/original_pdf_file/coal_resource_overview_of_coal_report(03_06_2009).pdf [Accessed October 2010].

WEINDORF, W., BUNGER, U. & SCHINDLER, J. 2003. *Comments on the paper by Baldur Eliasson and Ulf Bossel "The Future of the Hydrogen Economy: Bright or Bleak?"*. L-B-Systemtechnik GmbH. Ottobrunn, Germany. Available: http://www.mpfc.de/pdf/LBSTonBossel.pdf [Accessed October 2010].

WEISS, M., HEYWOOD, J., DRAKE, E., SCHAFER, A. & AU YEUNG, F. 2000. *On the road in 2020 - A life cycle analysis of new automobile technologies*. Report No. MIT EL-00-003. Energy Laboratory, Massachusetts Institute of Technology. MIT: Cambridge, MA. Available: http://web.mit.edu/energylab/www/pubs/el00-003.pdf [Accessed October 2010].

WIEDERKEHR, P., GILBERT, R., CRIST, P. & CAÏD, N. 2004. Environmentally Sustainable Transport (EST): Concept, Goal, and Strategy – The OECD's EST Project. *European Journal of Transport and Infrastructure Research,* 4**,** 11-25.

WOOLEY, R., RUTH, M., SHEEHAN, J., IBSEN, K., MAJDESKI, H. & GALVAZ, A. 1999. *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Predhydrolysis and Enzymatic Hydrolysis Current and Futuristic Scenarios*. National Renewable Energy Laboratory. Golden, Colorado.

ZAN, C., FYLES, J. W., GIROUARD, P. & SAMSON, R. A. 2001. Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in Soothern Quebec. *Agriculture, Ecosystems & Environment* 86**,** 135–44.



Hassan M. El-Houjeiri
Balliol College
Oxford, OX1 3BJ
Email: hassan.el-houjeiri@eng.ox.ac.uk