

Designing integrated local production systems: a study on the food-energy-water nexus

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Abstract

Centralised production of essential products and services based on fossil fuels and large scale distribution infrastructures has contributed to a plethora of issues such as deterioration of ecosystems, social-economic injustice and depletion of resources. The establishment of local production systems that deliver various products for local consumption (e.g. food, energy and water) by making the best use of locally available renewable resources can potentially alleviate unsustainable resource consumption. The main objective of this work is to develop process systems engineering tools combined with the concept of resource accounting using exergy for the design of such local production systems. A general design framework

comprising an optional preliminary design stage followed by a simultaneous design stage based on mathematical optimisation is proposed. The preliminary design stage considers each supply subsystem individually and allows insights into the potential interactions between them. The simultaneous design stage yields an optimal design of the local production system and has the capacity to include all design integration possibilities between the subsystems and generate a truly integrated design solution. The proposed methodology, which reflects generalised principles for designing local production systems, has been illustrated through a case study on the integrated design of the food-energy-water nexus for a designated eco-town in UK. It demonstrates the advantages of an integrated design of a system making use of local resources to meet its demands over a system relying on centralised supplies and a design without considering integration opportunities between subsystems.

Nomenclature

Sets

$a \in A$	Water sources
$ag \in AG$	Agricultural commodities
$b \in B$	Water sinks
$b' \in B'$	Regenerator water sinks
$c \in C$	Crops
$d \in D$	Food types
$i \in I$	Nutrient sources
$i' \in I'$	Imported nutrient sources
$i'' \in I''$	Locally produced nutrient sources
$j \in J$	Food sinks
$l \in L$	Livestock
$o \in O$	Operating flows
$r \in R$	Energy raw material
$s \in S$	Seasons
$x \in X$	Energy sources
$y \in Y$	Energy sinks

Parameters

$cb_{c,d}$	Conversion factor from crop c to food d
$cf_{l,d}$	Conversion factor from livestock l to food d
cod_b	Maximum allowable COD of water sink b , g COD/kg
$e_{o,j}$	Specific cumulative exergy of operating flows o to nutrient sink j , MJ/kg or MJ/MJ
e_r	Specific cumulative exergy of raw material r for energy production, MJ/kg
e^{cw}	Specific cumulative exergy of chemicals per unit wastewater, MJ/kg
e^{elw}	Specific cumulative exergy of electricity per unit wastewater, MJ/kg
e^{hew}	Specific cumulative exergy of heat per unit wastewater, MJ/kg
e^{ie}	Specific cumulative exergy of imported energy, MJ/MJ
e^{iel}	Specific cumulative exergy of total imported flows for producing electricity, MJ/kg
e^{ihe}	Specific cumulative exergy of total imported flows for producing heat, MJ/kg
e_x^{el}	Specific cumulative exergy for producing electricity from source x , MJ/kg
e_x^{he}	Specific cumulative exergy for producing heat from source x , MJ/kg
e_d^{imp}	Specific cumulative exergy of imported food d , MJ/kg
$e_{i',j}^{imp}$	Specific cumulative exergy of imported nutrient flows i' to nutrient sink j , MJ/kg
$E_{y,s}^{dem}$	Electricity demand at sink y per season s , GJ
ELD_d	Electricity demand per unit food d , MJ/kg
$F_{d,s}^{dem}$	Demand of food d in season s , t
FC	Nominal size of storage facility, t
$H_{i''}$	Harvest recovery rate of locally produced nutrient sources i''
$H_{y,s}^{dem}$	Heat demand at sink y per season s , GJ
H^{Max}	Maximum heat load in waste heat, GJ
HED_d	Heat demand per unit food d , MJ/kg
$L_{r,x}$	Land use per unit raw material r from source x , ha/MJ
L^{agri}	Total amount of agricultural land available, ha
L^{en}	Land available for energy production, ha
$M_{r,s}^{Av}$	Availability of raw material r in season s , MJ
$N_{j,s}^{dem}$	Demand of nutrient sink j in season s , kg
$nc_{i''}$	Nutrient content of locally produced nutrient sources i'' , kg N
$y_{c,s}$	Yield of crop c per season s
y_l	Yield of livestock l
RA_{ag}	Amount of residues or manure per unit of agricultural commodity, kg/kg
Ref	COD removal efficiency of treatment plant, %

RW_s	Amount of rainwater collected in season s , t
SED^{WA}	Electricity demand for treating unit wastewater, MJ/kg
SHD^{WA}	Heat demand for treating unit wastewater, MJ/kg
SL	Number of years of service life of storage facility, y
t	Time period over which heat is transferred, y
$T_{x'}^{in}$	Inlet temperature of heat source x' before heat exchange, °C
$T_{x'}^{out}$	Outlet temperature of heat source x' after heat exchange, °C
T_y^{in}	Temperature of heat sink y before heat exchange, °C
T_y^{out}	Temperature of heat sink y after heat exchange, °C
TD	Minimum temperature difference, °C
TE	Specific cumulative exergy of operating resources per unit accumulated crop, MJ/kg
UTD	Upper bound for temperature difference, °C
$W_{b,s}^{dem}$	Water demand of sink b in season s , t
WC_d	Amount of water required for agriculture per unit food d , kg/kg
WE	Amount of water required per energy produced, kg/MJ
WEG	Amount of wastewater generated per energy produced, kg/MJ
WGP_d	Amount of wastewater generated per unit food d , kg/kg
WP_d	Amount of water required for industrial processing per unit food d , kg/kg
$\eta_{x,r}^{el}$	Electrical efficiency of source x for raw material r
$\eta_{x,r}^{he}$	Heat efficiency of source x for raw material r

Variables

$A_{ag,s}$	Amount of agricultural commodity ag produced during season s , t
$A_{c,s}$	Amount of crop c locally produced in season s , t
$AC_{c,s}$	Amount of crop c accumulated at season s , t
$AC_{c,s-1}$	Amount of crop c accumulated from season $s-1$, t
AR_{s-1}	Amount of rainwater accumulated from season $s-1$, t
AW_s	Amount of rainwater available for consumption in season s , t
CA_c	Capital exergy resources for storage of crop c , GJ
CA^{rw}	Total capital exergy resources for rainwater storage, GJ
$cod_{b',s}$	COD of treated wastewater from treatment plant sink b' in season s , g COD/kg
$CP_{x',s}$	Heat capacity flow rate of source x' for season s , GJ/season
$CS_{y,s}$	Heat capacity flow rate of sink y for season s , GJ/season
$E_{x,grid,s}$	Amount of electricity from source x exported to grid in season s , GJ
$E_{x,y,s}$	Amount of electricity from source x to sink y in season s , GJ

ELD_s^{FD}	Total electricity demand of food processes in season s , GJ
ELD_s^{WA}	Total electricity demand of water processes in season s , GJ
$F_{d,s}^{crop}$	Amount of locally produced food d from crop in season s , t
$F_{d,s}^{imp}$	Amount of imported food d in season s , t
$F_{d,s}^{live}$	Amount of locally produced food d from livestock in season s , t
$F_{d,s}^{local}$	Amount of locally produced food d in season s , t
$H_{x,y,s}$	Amount of heat from source x to sink y in season s , GJ
$H_{x',y,s}$	Amount of heat exchanged between waste heat source x' and sink y in season s , GJ
HED_s^{FD}	Total heat demand of food processes in season s , GJ
HED_s^{WA}	Total heat demand of water processes in season s , GJ
L_c	Land use for production of crop c , ha/t
L_l	Land use for production of livestock l , ha/t
$M_{r,s}$	Amount of raw material r in season s , t
$N_{i',j,s}^{imp}$	Amount of imported nutrient flows i' to nutrient sink j in season s , t
$N_{i'',j,s}^{local}$	Amount of locally produced nutrient j from source i'' in season s , t
$OP_{c,s}$	Operating exergy resources for storage of crop c in season s , GJ
OSR	Optimal size of the rainwater storage tank, t
$Q_{x',y,s}$	Amount of heat energy from waste heat source x' to sinks y in season s , GJ
TC	Total capital resource exergy for storage facility, GJ
$U_{o,j,s}^{imp}$	Amount of imported operating flows o to nutrient sink j in season s , t or GJ
$W_{a,s}$	Total amount of water from source a in season s , t
$W_{a,b,s}$	Amount of water from source a to sink b in season s , t
$W_{a,b',s}$	Amount of wastewater from water sources a to the treatment plant sink b' in season s , t
$W_{b',b,s}$	Amount of wastewater from the treatment plant b' to water sinks b in season s , t
$W_{rw,b,s}$	Rainwater consumed by water sink b in season s , t
$WC_{c,s}$	Amount of locally produced crop c that is used in the same season s , t
WST_c	Size of crop c storage facility, t
W_s^{EN}	Total water requirement of energy processes in season s , t
W_s^{FD}	Total water requirements of food processes in season s , t
WG_s^{EN}	Total wastewater generation from energy processes in season s , t
WG_s^{FD}	Total wastewater generation from food processes in season s , t
$z_{x',y,s}$	Binary variable for heat integration between waste heat source x' to sink y in season s

1 Introduction

With the advent of industrialisation, the supply of energy and materials to meet human needs has been driven primarily by centralised production, harnessing economies of scale, based on fossil fuels and large scale distribution infrastructures. However, continuation of this mode of production coupled with growing population has led to a range of issues such as climate change, energy supply insecurity, deterioration of ecosystems and depletion of resources.

Local production systems have been regarded as one possible pathway towards sustainability (Royal Academy of Engineering, 2011). Though the challenges are global, they have local impacts and may affect each local system differently. This calls for the engineering of human-made systems with a focus on the rational use of locally available resources. Such systems require new design tools to allow decision makers to explore the roles of local details such as the significance of local resource use and the opportunities for interactions between co-located subsystems.

A local production system is defined as a network of heterogeneous processes, integrated in a synergistic manner to achieve a high degree of resource efficiency, potentially leading to improved economic viability while preserving the ecosystem (Martinez-Hernandez et al., 2015). It considers all types of production processes that can occur at a local scale for the production of products (e.g. food) and/or services (e.g. heat) to satisfy local demands. While these processes differ in technical natures, they share the following characteristics desirable from sustainability perspectives; it is precisely this set of common characteristics that is to be explored by this work. First of all, these systems offer the possibility to use renewable resources which can be captured or produced locally to meet demands of the local population. They also have the advantage of avoiding large transportation distances and the resulting impact on energy consumption and the environment. Furthermore, a localised paradigm

allows the processes and technologies to be developed or adapted according to local conditions. More importantly, the main opportunity that arises from developing locally integrated systems is the potential for symbiotic integration of multiple and distinct subsystems (e.g. water, energy, food, and ‘wastes’ arising from their supply and use) within the same locality in order to increase efficiency and sustainability.

The aim of this study is to propose a systematic approach to the design of integrated local production systems based on mathematical programming. Mathematical programming has been used broadly for process integration, such as the design of mass exchanger networks (El-Hawagi and Manousiouthakis, 1990), combined mass and heat exchanger networks (Srinivas and El-Halwagi, 1994), the integration of batch chemical processes (Smith, 2005), and, more recently, the design of heat exchanger networks using a two-step optimisation procedure incorporating detailed exchanger design (Short et al., 2016). On the other hand, insight-based approaches (Foo, 2007) which include techniques such as pinch analysis for heat integration (Linnhoff and Hindmarsh, 1983) and mass integration (El-Halwagi and Manousiouthakis, 1989) have been proved useful for integration of production processes. These methods have also been combined with mathematical programming into hybrid methods (Luo et al., 2009). More recent developments on insight-based and mathematical programming have been reviewed by Foo et al. (2012) who compiled process design and optimisation techniques recently developed for improving sustainability of industrial processes. Klemes et al. (2013) have also given an overview of achievements and future challenges in process integration while the review by Foo and Tan (2015) emphasized on approaches for the reduction of carbon emissions and environmental footprint. This current work focuses on the mathematical programming approach, which allows different synergies between different processes to be explored so as to generate a truly integrated design. This advantage has been exploited for the integrated design of local renewable resources for

energy supply (Kostevsek et al., 2015) and the simultaneous design of energy and water networks within the same production system (Martin and Grossmann, 2015) but not for the integration between multiple production systems (e.g. food production, water treatment, energy production). The conventional way of designing production systems rarely explores the potential for integration with other production systems to satisfy local demands in the most sustainable manner, but this could be addressed by local production systems.

Localised production is closely related to eco-industrial parks (EIPs) under the broad concept of industrial symbiosis (IE) which advocates the leveraging of the synergies between geographically co-located industrial processes (Chertow and Ehrenfeld, 2012). Mathematical optimisation methods have proved useful for designing EIPs (Boix et al., 2015). More specifically, an optimisation approach has been formulated for the cost effective design of water and wastewater treatment among industries in an EIP (Lovelady and El-Halwagi, 2009), on the maximisation of economic performance for the design of bioenergy-based industrial symbiosis system (Ng et al., 2014), the optimisation of material flow by-products as feedstock for other industrial processes (Cimren et al., 2012) and more recently on the fuzzy optimisation of waste-to-energy among several plants contained in an EIP (Takshiri et al., 2015). On the other hand, some other studies have focused on regional supply chain optimisation such as the optimisation of a regional renewable energy supply chain from biorefinery operations (Lam et al., 2010), cellulosic ethanol supply chain optimisation at the county level (You et al., 2011) and the optimisation of water supply chain across different regions (Aviso et al., 2011). Local integrated production systems, as explored in this work, clearly should share the beneficial features of EIPs or IE systems in general, such as the exchange of wastes, energy and water between industrial processes. However, the concept of local production system has a distinctive emphasis on local resources and demands and on the holistic consideration of all types of agricultural, industrial and municipal processes to take

place at the locality of concern. In contrast, the work on IE systems including EIPs generally does not have a focus on the "local" dimension in terms of natural resources and societal demands, and rarely considers agricultural processes. The design of regional supply chains, on the other hand, often addresses one or very a few specific products such as energy and fuels, not aiming to explore the synergies in meeting other regional demands. Therefore, while sharing commonalities with existing work on eco-industrial parks and regional supply chains in terms of pursuing higher resource efficiencies through optimisation and integration, the design of local production systems as studied in this work represents a rather different decision problem in terms of aim and scope that are meant to support the expected economic paradigm shift towards localised production, with the potential benefits of a sustainable development path as highlighted earlier.

A local production system will comprise a non-linear structure with waste and by-products looped back into the system and synergies exploited and will require the design of the system and its components to be highly tuned to the local settings. In this paper, a systematic mathematical modelling-based approach is proposed for designing local production systems that, given a set of locally available resources, selects and integrates a combination of production or treatment processes to meet given local population needs. It adopts a life cycle approach accounting for resource consumption using cumulative exergy consumption as an indicator of resource intensity for the imported flows as well as for capital resources and environmental remediation efforts. Furthermore, this is the first time that such a systematic approach is applied for designing the local food-energy-water nexus.

2 Methodology for designing integrated local production systems

2.1 Design problem statement and quantification of resource consumption

The design of local production systems considers the production of multiple products and services to satisfy local demands within the capabilities of the local environment and ecosystems (e.g. groundwater abstraction limit). Due to the different nature of the resources used in a system that integrates heterogeneous components, it is desirable to adopt a unifying quantity such as exergy (Sciubba and Wall, 2007); defined as the available energy of a resource to do useful work. In this work, cumulative exergy consumption (CExC) will be used, which is an approach also applied in other contexts (Allwood et al., 2011). CExC in delivering a service is the sum of the exergy of all types of resources required from extraction to the point where they are used. The problem of designing local production systems can be generally stated as:

Given a set of demands by the population in a locality and the availability of local and external resources, determine the combination of a set of processes and activities which can meet such demands so that the total cumulative exergy consumption is minimised while observing all necessary constraints.

In this work, local production systems will be designed with a strong focus on using locally available resources, yet with the recognition that not all resources can or should necessarily be provided locally, also considering the possibility of having production surpluses for export and discharges to the environment. Therefore, the designs are expected to generally result in a mixture of local, imported and exported resource flows that allow satisfying local demands in a resource efficient manner.

Following the above principle, the design objective (for minimisation) can be stated as the sum of the CExC of every flow that goes into (i) the local production system and (ii) the technological or environmental processes required for treating the effluents of (i) to the extent that, in principle, no harm is made to the environment, or, in practical terms, a certain set of environmental regulations are met. When the production system exports a valuable product, its resource content, valued by the average CExC of the product of the same nature as available in the external market, is treated as resource “credit” of the system. This credit is deducted from the total resource consumption by the local production system, leaving the design objective as to minimise the net resource consumption for meeting the local demand.

When quantifying the CExC of flows, two different types of processes from which the flows are originated have been distinguished (Leung Pah Hang et al., 2016) to avoid unnecessary complexity while maintaining consistency. In order to facilitate subsequent discussions in the paper, Flow-generating processes have been classified into two types. Type-I processes are defined as those that can be affected by human decisions, while Type-II processes are those that typically are not under human control. Flows from Type-I processes (e.g. grid electricity) would be accounted by their full CExC while flows from Type-II processes (e.g. wind, sunlight and ores) by their exergy content fully defined by their physical nature and any further exergy consumption for their extraction and processing. The resource value of flows from Type-II processes should be considered when there is a need for recognising that these resources have alternative competing uses. However, the full CExC for the formation in the natural environment of these flows will not be taken into consideration as they occur independently from human intervention.

The scope of the proposed method is to optimise resource consumption from a technical perspective; cumulative exergy consumption is used because exergy is a unifying quantity that can represent material, energy and non-energetic streams. Nevertheless, the modelling

approach to capturing the interconnections between different processes and subsystems while taking into account local resources and demands may be applied with other objective functions and constraints pertaining to economic costs, social benefits, regulatory considerations and broader environmental impacts.

2.2 Overview of the proposed approach

Figure 1 depicts the steps in the proposed methodological framework for the design of integrated local production system based on mathematical programming.

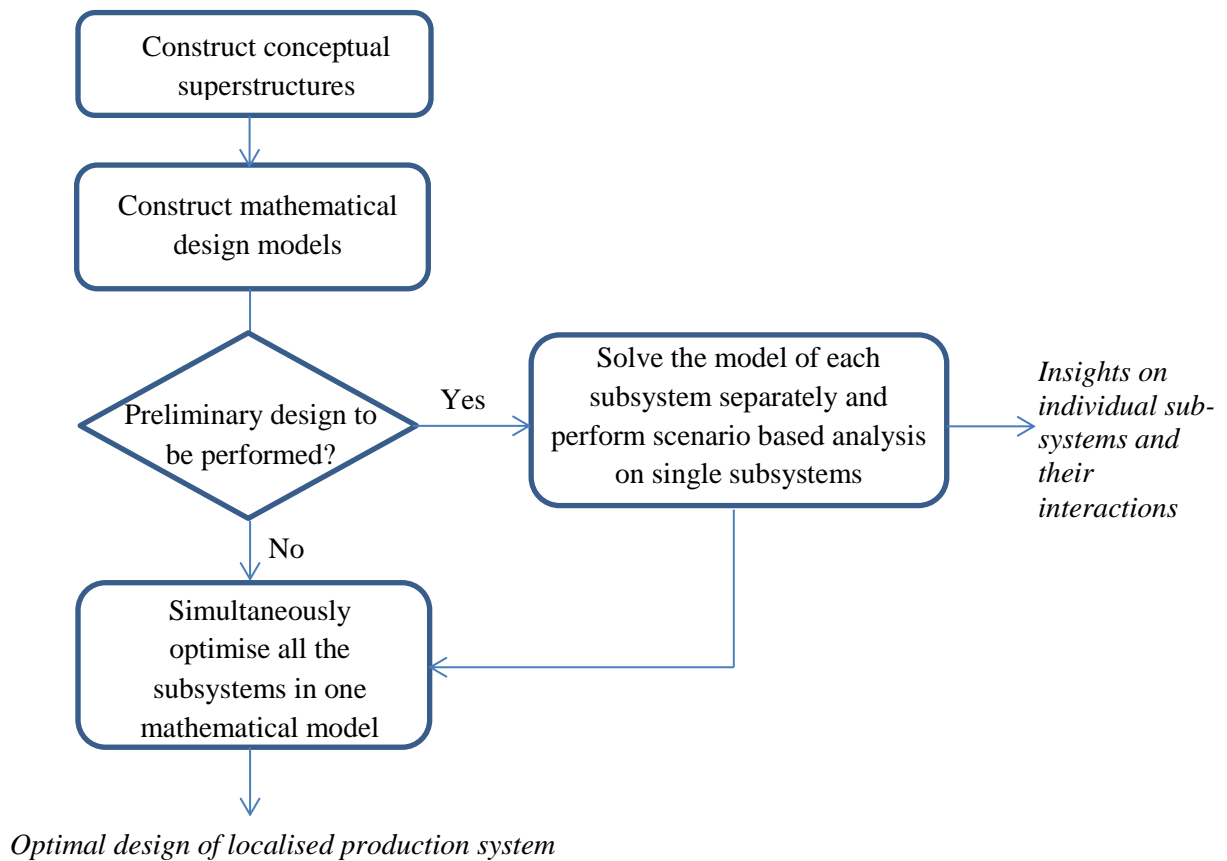


Figure 1: Methodological framework for designing a localised synergistic production system

Given a set of demands by the population in a locality and the availability of local and external resources, the first step is to construct conceptual superstructures (section 2.3), to identify possible processes and flows to introduce within individual subsystems and the

possible exchanges between these subsystems. Mathematical models are then constructed (section 2.4) according to the conceptual superstructures with the aim of minimising cumulative exergy resource consumption. With the models of individual subsystems, an optional preliminary design analysis (section 2.5) can be carried out if it is desirable by the decision-makers to gain an initial understanding of design alternatives. The last step of the approach (section 2.6) solves the mathematical model of the entire system to achieve integrated optimal design.

As stated above, the design procedure starts with a pre-defined geographical scope, i.e. that of the locale of concern. This will in turn determine (i) the population for which the demands to be met and (ii) the natural resources to be tapped in, thus defining the system boundary. In practice, the scope of the targeted locale will depend on the intention of the decision makers or their perception of the feasibility for implementing an integrated design. This may settle to an area under the direct governance of a local or regional planning body or one under direct influence of a community group, e.g. a village, a town, or a county in the UK context. While the proposed approach does not determine the system boundary, the decision makers could apply the approach to alternative scopes to assess the impact, leading to an optimal scope for designing and eventually implementing a local integrated production system.

2.3 Conceptual construction of superstructures

Superstructures are used to represent design options by means of sources, sinks and their connections. Based on the generally accepted definition of source and sink in process integration (El-Halwagi, 2011), in this work, a source refers to a material or energy flow, while sinks are defined as those components of the system that can receive flows, which either process them to generate new flows or act as terminating points for flows (e.g. consumption by local population or discharge into the environment). As presented before, a

local production system will be made up of various interconnected subsystems. These subsystems can be for example the food production subsystem, the energy subsystem, the water subsystem and so on. Each of these subsystems contains production or treatment processes. Construction of superstructures involves the following steps:

- (1) Identify all subsystems in the local production system, to ensure that there is scope for exchange and integration between different subsystems.
- (2) Determine all the possible sources and sinks in each subsystem. Figure 2 (a) illustrates the superstructure of sources and sinks in a single subsystem. As shown in Figure 2(a), a source (i) can be an external incoming flow (e.g. $i=1$), an internal resource flow from the local environment (e.g. $i=2$), a discharge flow to the environment (e.g. $i=6$), a flow exchanged between two internal processes (e.g. $i=3, 4$), or an export flow of surplus product to external systems (i.e. $i = 5$). On the other hand, a sink (j) can represent a process (e.g. $j=1, 2$), local consumption (e.g. $j=5$), the local environment as the destination of discharge ($j=4$) or an external system as the destination of export (e.g. $j=3$). Note that the processes are those taking place within the system boundary of the local system leading to products that can satisfy local demands.
- (3) Establish integration opportunities within and between subsystems by means of exchanges of various sources between different sinks, as illustrated in both Figures 2(a) and 2(b). Figure 2(b) which shows the potential sources and sinks in a system comprising two subsystems connected together; particularly illustrates how exchanged sources between the subsystems become potential sources for subsystem A (e.g. $i=5, 9$) and subsystem B (i.e. $i= 2, 3$). Look specifically for options for recycling and exchange of locally available flows based on their content (e.g. agricultural residues can be used as energy feedstock due to high calorific value or as feedstock for livestock due to its nutritional content).

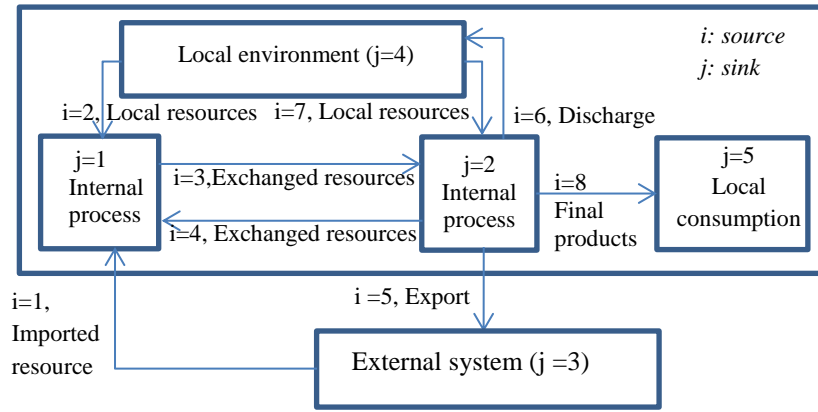


Figure 2(a): Illustrative superstructure of a single (sub-) system

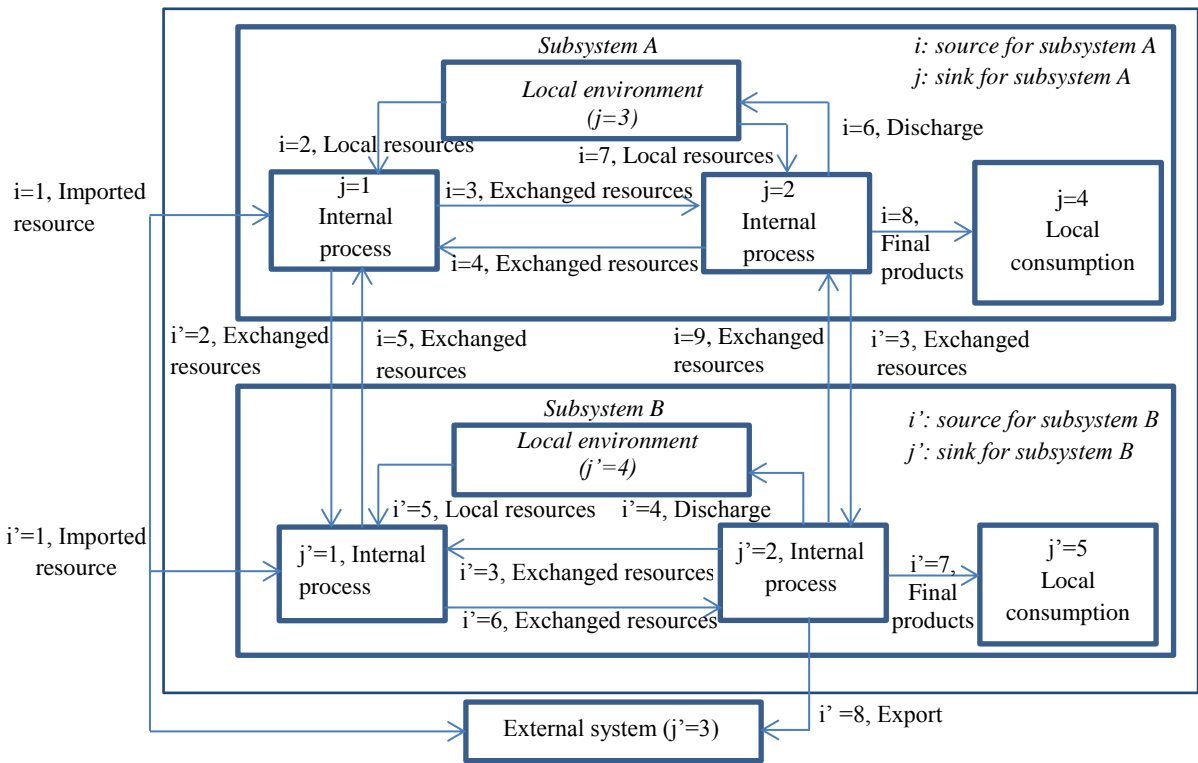


Figure 2(b): Generic superstructure representation of combined systems

The conceptual construction of superstructures is exemplified further for the food-energy-water nexus in Section 3.1.

2.4 Constructing the mathematical optimisation model for each subsystem

An optimisation model is formulated for each subsystem based on their superstructure and should consist of:

- 1) An objective function that minimises the net resource consumption for each subsystem.
- 2) A set of equations that describe the technical constraints, behaviour of the processing units and the interconnections between various sinks as expressed in the superstructure.
- 3) Ecological constraints that limit the use of locally available resources and the discharge of waste streams to the environment within the ecosystem's capacity for resource re-generation and waste assimilation.
- 4) Time slice and storage to provide a suitable treatment of the temporal variations in supply and demand. Local storage may be required to reconcile the temporal mismatch between varying local supply and demand, affected by the connectedness of the locale with other local systems or a central system for distribution. The temporal variations within the system need to be properly handled by the mathematical model, possibly through time slicing (Becker and Marechal, 2011) to allow variations to occur between different time slices. The size of time slice, which represents the model's temporal resolution, should match with the intended use of storage and may vary between as short as hourly (e.g. storing wind or solar electricity for a local system not connected to a central grid) and as long as seasonally (e.g. rain water collection where supply and demand variations are largely seasonal). When different sets of supply and demand have diverse time characteristics, the finest size of time slice will be adopted for the whole system.

The construction of the optimisation model is illustrated in section 3.2.

2.5 Preliminary design analysis

Once the mathematical models for individual subsystems have been built, a preliminary design analysis could be carried out if it is desirable to gain an initial understanding about possible designs. This could also be useful when dealing with existing infrastructure and the design is more for retrofitting purposes, or when systems are implemented separately in stages with a view to develop systems integration in the future. Any of these cases may benefit from an incremental understanding of the improvement potential. The preliminary design analysis broadly includes using the separate optimisation models for individual subsystems and performing scenario analysis. The specific stages in the preliminary design analysis could include:

- (1) Use conventional input flows such as grid electricity and natural gas derived heat in the initial design of a subsystem and report its objective function and decision variables.
- (2) Vary the source of input flows (e.g. energy supply from biomass CHP instead of grid electricity) to the subsystem and analyse the impacts on its objective function and decision variables.
- (3) Design the other subsystems by using the same source of input flows as in the previously designed subsystem where relevant. If the other subsystems have a logical connection with the previous subsystem, consider satisfying the new demands resulting from the previous subsystem in the design of the other subsystems. For instance, if the food subsystem is designed first, the water and energy demands of the food processes need to be considered in the subsequent design of the water and energy subsystems respectively, in addition to other local water and energy demands.

- (4) Perform a scenario analysis by repeating (2) and (3) with different sets of input, and analyse the outcome of these scenarios.

Such preliminary analyses could help to understand the interactions between the various components of a local production system and how these might affect the overall resource consumption. In particular, the results obtained from the preliminary design analysis may provide insights into the balance of exchange flows between individual subsystems and the trade-offs between using imported conventional resources and locally available resources.

2.6 Constructing and solving a simultaneous design model

To eventually identify the optimal, integrated design, all the superstructures of the subsystems are combined into a single superstructure by considering the integration opportunities. Based on the combined superstructure, illustrated earlier in Figure 2(b), one mathematical optimisation model is then formulated and solved. The elements of the integrated system model are similar to those of individual subsystems as presented in section 2.4. However, the objective function now is to minimise total net resource consumption and does not include any intermediate flows (internally exchanged) between subsystems. Besides, the quantity of demand of each subsystem for the other subsystems and the characteristics of the supply from one subsystem to the others become unknown and will be determined via optimisation.

The simultaneous approach will generate the optimal integrated design of a local production system as a whole. In comparison to the preliminary analysis, it considers all design integration options simultaneously across all subsystems. This approach is essential for revealing the benefits of an integrated local production system on resource efficiency and circularity as compared to the practice of designing distinct subsystems in silos.

3 Building design models for food-energy-water nexus

The methodology for constructing the design models is illustrated by the food-energy-water nexus. The nexus concept has been broadly used to identify the issues arising from the interconnectedness between food, energy and water subsystems. In addition, the nexus has been used as a framing for systems analysis albeit mostly at the regional, national and global scales (FAO, 2014). The importance of this nexus has been clearly recognised for sustainable development and national security in the UN (UN WATER, 2104), FAO, governments and organisations around the world (NEXUS, 2015). Though these three sectors are inextricably linked, as actions in one sector have impacts in one or both of the others, these areas have too often been considered in isolation (FAO, 2014). Thus, there is a clear need to look at them holistically and develop tools that consider their interdependencies (Machell et al., 2015). This opens up opportunities for process system engineering research (Garcia and You, 2016). While existing tools such as modelling and Life Cycle Assessment have been applied to study various parts of the nexus, new frameworks are required to analyse complex relationships embedded in such systems (Keairns et al., 2016), using a systematic approach to address the resulting challenges associated with risks from a supply chain perspective (Irabien and Darton, 2015) and systems integration (Wolfe et al., 2016). . In our work, this is the first time that such a systematic view is applied for designing a food-energy-water nexus at the local scale. Therefore, nexus in this work refers to a system that takes advantage of opportunities for synergy and integration arising from closely connected and geographically co-located subsystems for food, energy and water production.

3.1 Building superstructures

The models presented in this section have assumed specific food types and energy generation technologies, originated from a case study to be presented in Section 4, to aid the

understanding of the conceptual superstructure. With minor adaptations, the mathematical models can readily be applied to cope with arbitrary system components.

3.1.1 Superstructure for food production subsystem

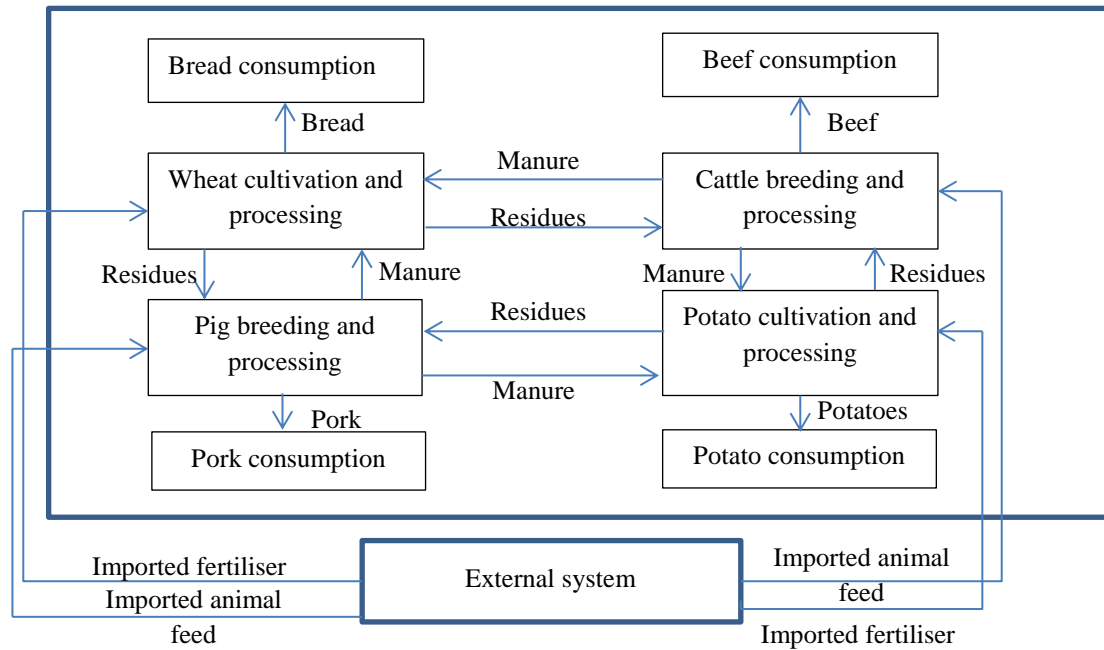


Figure 3: Superstructure for food production subsystem

The superstructure for the food production subsystem is shown in Figure 3. The food types chosen as examples are bread, potatoes, beef and pork. The sources include imported fertilisers, animal feed and locally produced nutrient flows from manure or crop residues while internal processes (as sinks) are those for bread, potatoes and beef and pork production.

3.1.2 Superstructure for water production system

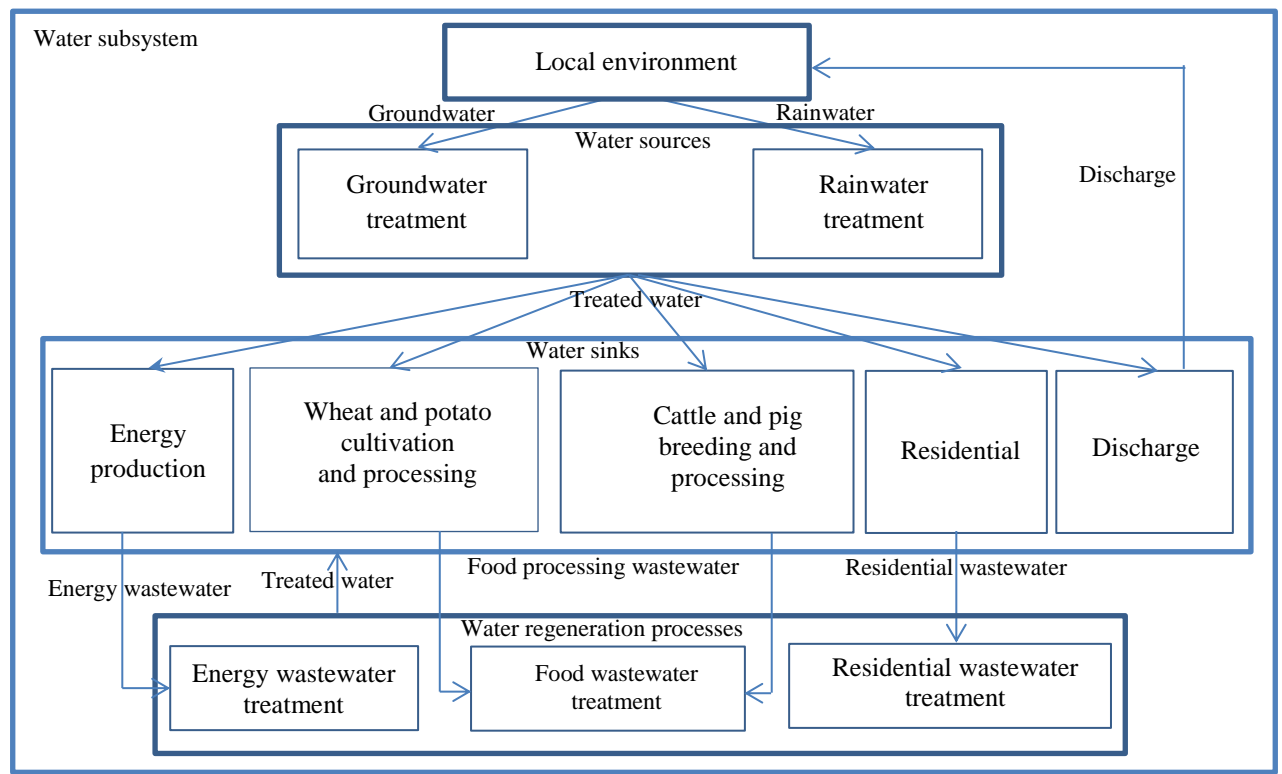


Figure 4: Superstructure for water production subsystem

Figure 4 illustrates the superstructure for water production subsystem. The possible water sources include water of varying quality (e.g. chemical oxygen demand (COD)) from food and energy production subsystems, treated residential wastewater, groundwater and rainwater. The sinks considered are the food and energy subsystems and the residential sector. Water treatment operations (as “intermediate” sinks) were included and acted as regeneration processes before water sources could be made available for use in the “final” sinks.

3.1.3 Superstructure for energy production subsystem

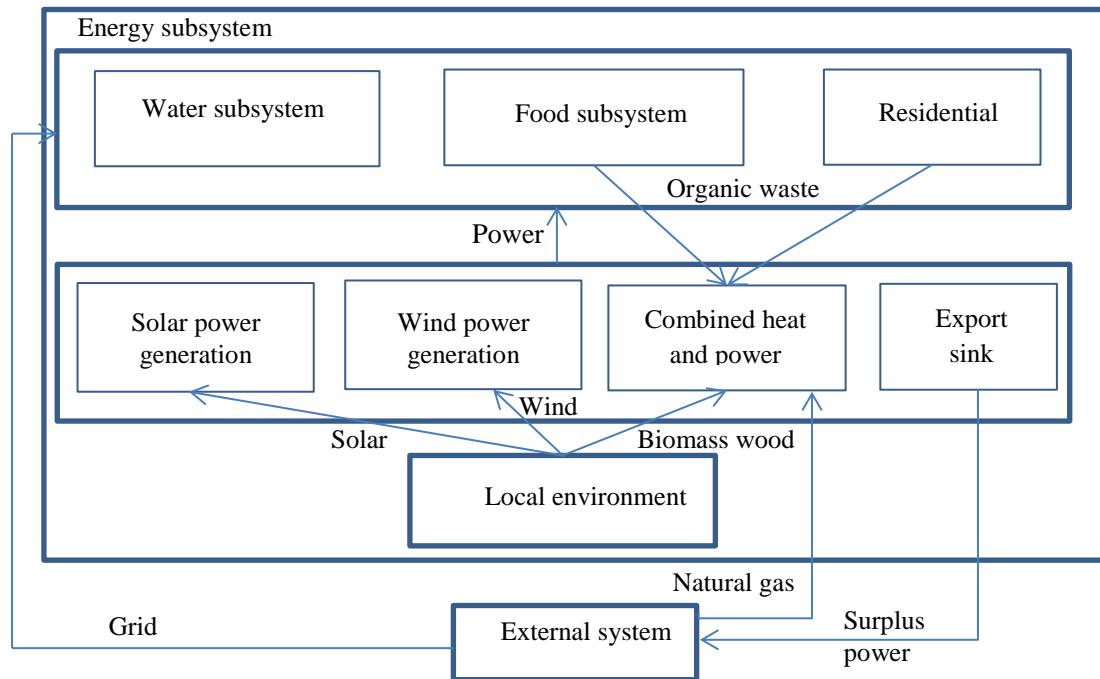


Figure 5: Superstructure for electricity production

Figures 5 and 6 represent respectively the electricity and heat energy sources and sinks considered for the design of the energy subsystem. The energy sources are grid electricity, electricity from wind and solar sources, heat from natural gas boilers, and heat and power from Combined Heat and Power (CHP) based on biomass, organic waste or natural gas. Waste heat sources considered were low temperature (LT) waste heat available from all CHPs (apart from the main heat flows produced) and food production processes which will be lost if not recovered. The sinks were food and water production processes and the residential sector and the possibility for export of electricity to the grid.

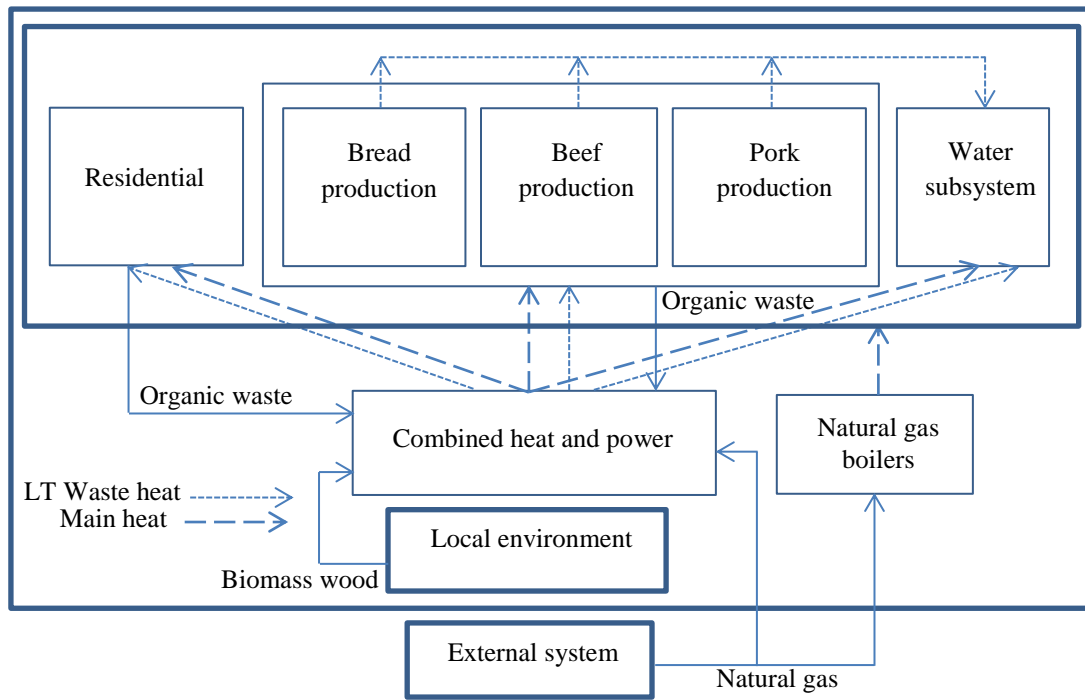


Figure 6: Superstructure for heat production

3.1.4 Superstructure for simultaneous food, energy and water design

Figure 7 shows the superstructure comprising representative sources and sinks for all the three subsystems. The important exchange of flows between the three subsystems include energy flows from the energy subsystem to the food and water subsystems and water flows from the water subsystem to the food and energy subsystems. Wastewater generated from the food and energy subsystems could be treated in the water subsystem and organic waste from food subsystem could be used as a potential energy source for the energy subsystem.

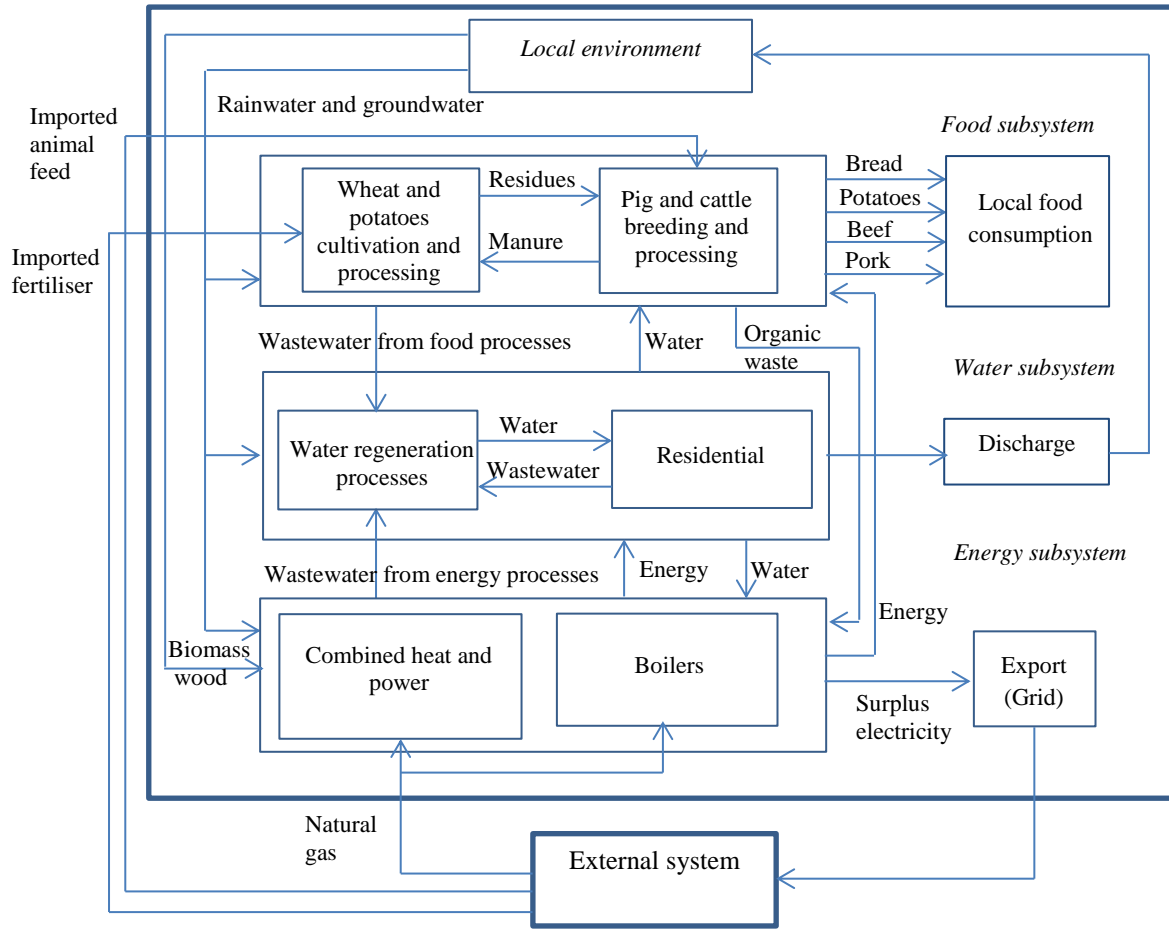


Figure 7: Superstructure for integrated food, energy and water system

3.2 Mathematical formulation for the preliminary design analysis

In this section the model formulation for a preliminary design analysis is presented. The time period of one year is chosen as basis for the model. The local system studied is well connected to the grid, so energy storage was not considered, and thus a seasonal time slice that can match seasonal storage for agricultural crops and rainwater collection has been adopted for the design. The starting season for design was taken to be summer.

3.2.1 Mathematical formulation of food production system

The optimisation problem for the design of a food production subsystem is to minimise the total cumulative exergy consumption for meeting the local food demand. This objective

function comprises resource consumption associated with imported food, nutrients, operating flows and crop storage, as formulated in Equation (1).

Minimise objective function:

$$TEF = \sum_{s \in S} \sum_{d \in D} e_d^{imp} F_{d,s}^{imp} + \sum_{s \in S} \sum_{j \in J} \sum_{i' \in I'} e_{i',j}^{imp} N_{i',j,s}^{imp} + \sum_{s \in S} \sum_{j \in J} \sum_{o \in O} e_{o,j}^{imp} U_{o,j,s}^{imp} + \sum_{c \in C} CA_c + \sum_{s \in S} \sum_{c \in C} OP_{c,s} \quad (1)$$

TEF is the total cumulative exergy consumption for the food production subsystem, e_d^{imp} is the specific cumulative exergy of imported food d , $F_{d,s}^{imp}$ the amount of imported food d in season s , $e_{i',j}^{imp}$ the specific cumulative exergy of imported nutrient flow i' to sink j , $N_{i',j,s}^{imp}$ the amount of imported nutrient flow i' to sink j in season s , $e_{o,j}$ the specific cumulative exergy of operating flow o to sink j , $U_{o,j,s}^{imp}$ the amount of operating flow o to sink j in season s , CA_c the capital exergy resource for storage of crop c storage and $OP_{c,s}$ the operating exergy resource for crop storage in season s .

The optimisation is subject to the following constraints:

1) Final food demand balance

The food demand balance for each season by the local population is given in Equation (2).

$$F_{d,s}^{imp} + F_{d,s}^{local} = F_{d,s}^{dem} \quad (2)$$

$F_{d,s}^{local}$ is the amount of locally produced food d in season s , $F_{d,s}^{imp}$ the amount of imported food d in season s and $F_{d,s}^{dem}$ the demand of food d in season s . $F_{d,s}^{local}$ can be produced from either livestock or crop.

$F_{d,s}^{live}$ is the amount of locally produced food d from livestock l and can be determined from the yield of livestock, y_l , the conversion factor $cf_{l,d}$ from livestock l to food d , and the land use for livestock production L_l as given by Equation (3):

$$F_{d,s}^{live} = L_l y_l cf_{l,d} \quad \forall l \in L \quad (3)$$

The amount of crop c to be locally produced in any season, $A_{c,s}$, can be determined through Equation (4).

$$A_{c,s} = L_c y_{c,s} \quad \forall c \in C, s \in S \quad (4)$$

with L_c being the land use for crop production and $y_{c,s}$ the crop yield per season s .

The amount of locally produced food product d from a particular crop during season s , $F_{d,s}^{crop}$, can be determined through the amount of the locally produced crop c that is used in the same season s , $WC_{c,s}$, and the conversion factor $cb_{c,d}$ from crop to food product as shown in Equation (5).

$$F_{d,s}^{crop} = cb_{c,d} WC_{c,s} \quad \forall c \in C, s \in S \quad (5)$$

2) Land availability constraint

The land occupied by livestock L_l and crops L_c must not exceed the total amount of agricultural land available L^{agri} as given in Equation (6).

$$\sum_{c \in C} L_c + \sum_{l \in L} L_l \leq L^{agri} \quad (6)$$

3) Nutrient requirement for crop and livestock

The sum of the imported and locally produced nutrient flows (denoted by i) should be equal to the total nutrient demand of each sink j in each season s as shown in the nutrient balance for crops and livestock in Equation (7)

$$\sum_{i' \in I'} N_{i',j,s}^{imp} + \sum_{i'' \in I''} N_{i'',j,s}^{local} = N_{j,s}^{dem} \quad \forall j \in J, s \in S \quad (7)$$

with $N_{i'',j,s}^{local}$ being the amount of locally produced nutrient from source i'' (e.g. from crop residues or manure) in season s and $N_{j,s}^{dem}$ the demand of sink j in season s . $N_{i'',j,s}^{local}$ can be determined through Equation (8)

$$\sum_{j \in J} N_{i'',j,s}^{local} = nc_{i''} A_{ag,s} RA_{ag} H_{i''} \quad \forall i'' \in I'', ag \in AG, s \in S \quad (8)$$

with $nc_{i''}$ being the nutrient content of locally produced nutrient i'' , $A_{ag,s}$ the amount of agricultural commodity (i.e. crop or livestock) ag produced locally, RA_{ag} the ratio of amount of residues or manure generated per unit output of ag and $H_{i''}$ the harvest recovery rate of locally produced nutrient i'' taking into account that some residues need to be left in the field to maintain the nutrient soil balance.

4) Crop storage considerations

The amount of the locally produced crop c that is used in season s , $WC_{c,s}$, should not exceed the sum of the amount of crop c produced in that season, $A_{c,s}$, and the amount of crop c accumulated from previous seasons, AC_{s-1} as given in Equation (9).

$$WC_{c,s} \leq A_{c,s} + AC_{c,s-1} \quad \forall c \in C, s \in S \quad (9)$$

The accumulation of crop c by the end of any season s , $AC_{c,s}$ can be determined by the difference between the sum of the amount of crop c (i) produced in season s , $A_{c,s}$, (ii)

accumulated in the previous season, $AC_{c,s-1}$, and (iii) consumed in season s , $WC_{c,s}$ as given in Equation (10).

$$AC_{c,s} = A_{c,s} + AC_{c,s-1} - WC_{c,s} \quad \forall c \in C, s \in S \quad (10)$$

Since summer is the starting season for design, it is assumed that there is no crop accumulated from the previous season at the beginning of summer. Thus, $AC_{c,s-1} = 0$ for s denoting summer.

The size of crop storage facility WST_c , should accommodate the maximum accumulated crop level during the year as given in the inequality constraint (11).

$$WST_c \geq AC_{c,s} \quad \forall s \in S \quad (11)$$

The capital exergy resources for crop storage for a year, CA_{cr} , is estimated by Equation (12)

$$CA_{cr} = \frac{TC}{SL} \frac{WST}{FC} \quad (12)$$

with TC being the total capital resource exergy for the storage facility with a nominal size of FC , and SL is the number of years of the service life of the storage facility.

The operating exergy resources for crop storage, $OP_{c,s}$, is given in Equation (13).

$$OP_{c,s} = TE AC_{c,s} \quad \forall c \in C, s \in S \quad (13)$$

TE is the specific cumulative exergy of operating resources per unit accumulated crop.

3.2.2 Mathematical formulation of water production system

The optimisation problem for the design of a water production subsystem is to meet local water demands while minimising total exergy resource consumption of electricity, heat and chemicals used for treating water sources to sinks as given in Equation (14).

Minimise objective function:

$$TEW = \sum_{s \in S} \sum_{b \in B} \sum_{a \in A} (e^{elw} + e^{hew} + e^{cw}) W_{a,b,s} + CA^{rw} \quad (14)$$

TEW is the total cumulative exergy consumption for the water production subsystem, e^{elw} is the specific exergy resource of electricity, e^{hew} is the specific exergy resource of heat and e^{cw} is the specific exergy resource of chemicals per kg of wastewater treated. $W_{a,b,s}$ is the amount of water from source a to sink b in season s and CA^{rw} the total capital exergy resources for the rainwater storage facility.

The optimisation is subject to the following constraints:

1) Mass balance around water sources

The total amount of water that can be supplied from source a to the sink b is given by

Equation (15):

$$\sum_{b \in B} W_{a,b,s} = W_{a,s} \quad \forall a \in A, s \in S \quad (15)$$

where $W_{a,b,s}$ is the amount of water from source a to sink b in season s and $W_{a,s}$ the total amount of water from source a in season s .

2) Concentration balance with respect to chemical oxygen demand (COD) levels

The plant treats wastewater generated from various sources before they can be used in the sinks as each of the water sinks can only accept water of a certain level of COD. The concentration balance around the wastewater treatment plants (regenerators) adapted from Sadhukhan et al. (2014) is given in Equation (16):

$$(1 - Ref) \sum_{a \in A} cod_a W_{a,b',s} = cod_{b',s} \sum_{b \in B} W_{b',b,s} \quad \forall b' \in B', s \in S \quad (16)$$

where Ref is the COD removal efficiency of the treatment plant, cod_a the COD of the wastewater from source a , $W_{a,b',s}$ the amount of wastewater from source a to the treatment plant sink b' in season s , $W_{b',b,s}$ the amount of wastewater from the treatment plant b' to sink b in season s and $cod_{b',s}$ the COD of the treated wastewater from treatment plant sink b' in season s . Equation (16) introduces non-linearities in the water model as a result of COD contaminant mixing which gives rise to a bilinear term from the multiplication of unknowns of the outlet flow and concentration from the treatment plant.

3) Quality constraint

The maximum allowable COD of each sink b , cod_b should not be exceeded by the COD level resulting from the mixing of various supplying sources, as indicated by Equation (17):

$$\sum_{a \in A} cod_a W_{a,b,s} \leq cod_b W_{b,s}^{dem} \quad \forall b \in B, s \in S \quad (17)$$

where $W_{b,s}^{dem}$ is the water demand of sink b in season s .

4) Mass balance around water sinks

The total amount of water supplied from source a to sink b in season s should balance its water demand in that season, $W_{b,s}^{dem}$, as given in Equation (18).

$$\sum_{a \in A} W_{a,b,s} = W_{b,s}^{dem} \quad \forall b \in B, s \in S \quad (18)$$

5) Rainwater storage considerations

The amount of rainwater available for consumption in season s , AW_s can be determined through Equation (19):

$$AW_s = RW_s + AR_{s-1} \quad \forall s \in S \quad (19)$$

where RW_s is the amount of rainwater collected in season s and AR_{s-1} is the amount of rainwater accumulated from the previous season $s-1$.

Rainwater accumulated by the end of season s , AR_s can be determined through Equation (20) by the difference between (i) the sum of rainwater collected in season s (RW_s) and the amount of rainwater accumulated from the previous season $s-1$ (AR_{s-1}) and (ii) the rainwater consumed in season s :

$$AR_s = RW_s + AR_{s-1} - \sum_{b \in B} W_{rw,b,s} \quad \forall s \in S \quad (20)$$

where $W_{rw,b,s}$ is the amount of rainwater supplied to sink b in season s .

It is assumed that stored rain water is always fully consumed within the year of storage. Thus for summer, which is the starting season for design, $AR_{s-1} = 0$.

The optimal size of the rainwater storage tank, OSR , should accommodate the maximum rainwater level available for consumption at any season during the year (AW_s) as given in the inequality constraint (21).

$$OSR \geq AW_s \quad \forall s \in S \quad (21)$$

The capital exergy resources for rainwater storage, CA^{rw} , can be determined through Equation (22):

$$CA^{rw} = \frac{TC}{SL} \frac{OSR}{FC} \quad (22)$$

where TC is the total capital resource exergy for the storage tank with a nominal size of FC , and SL is the number of years of the service life of the tank.

3.2.3 Mathematical formulation of energy production network

The optimisation problem for the design of an energy production subsystem is to minimise the net total cumulative exergy consumption meeting the local energy demand, comprising resource consumption associated with raw material, capital and operating resources minus the cumulative exergy consumption avoided by exporting any surplus local power generation to the grid as formulated in Equation (23). Capital resources (i.e. those consumed for building equipment and production facilities) for CHPs, wind turbines and solar panels were included as these technologies consume relatively negligible operating resources; making their capital resources relatively significant.

Minimise objective function:

$$TEE = \sum_{s \in S} \sum_{r \in R} e_r M_{r,s} + \sum_{s \in S} \sum_{y \in Y} \sum_{x \in X} e_x^{el} E_{x,y,s} + \sum_{s \in S} \sum_{y \in Y} \sum_{x \in X} e_x^{he} H_{x,y,s} - \sum_{s \in S} \sum_{x \in X} e^{grid} E_{x,grid,s} \quad (23)$$

where TEE is the total net cumulative exergy consumption for the energy production subsystem, e_r is the specific cumulative exergy of the raw material (i.e. energy input including grid electricity) r , $M_{r,s}$ the amount of raw material r in season s , e_x^{el} the specific total (i.e. operating and capital) cumulative exergy consumption for producing electricity from energy source x , $E_{x,y,s}$ the amount of electricity from energy source x to energy sink y in season s , e_x^{he} the specific total (i.e. operating and capital) cumulative exergy consumption for producing heat from energy source x , $H_{x,y,s}$ the amount of heat from source x to sink y in season s , e^{grid} the cumulative exergy of grid electricity and $E_{x,grid,s}$ the amount of electricity from source x exported to grid.

The optimisation is subject to the following constraints:

1) Electricity demand constraint for each sink

The supply of electricity from all electricity energy sources for local consumption should balance the electricity demand at energy sink y per season s , $E_{y,s}^{dem}$, as shown in Equation (24).

$$\sum_{x \in X} E_{x,y,s} = E_{y,s}^{dem} \quad \forall y \in Y, s \in S \quad (24)$$

2) Heat demand constraint for each sink

The supply of heat from all heat energy sources should balance the heat demand at energy sink y per season s , $H_{y,s}^{dem}$, as given in Equation (25).

$$\sum_{x \in X} H_{x,y,s} = H_{y,s}^{dem} \quad \forall y \in Y, s \in S \quad (25)$$

3) Raw material availability constraint

The raw material availability constraint is given in Equation (26):

$$\sum_{x \in X} M_{r,x,s} \leq M_{r,s}^{Av} \quad \forall r \in R, s \in S \quad (26)$$

where $M_{r,x,s}$ is the amount of raw material r consumed for energy source x in season s , $M_{r,s}^{Av}$ the availability of raw material r in season s . Equation (26) applies to biomass, organic waste, solar and wind energy available for energy production, assuming seasonal averages are suitable for quantifying availability.

4) Land availability constraint

The total land use by the energy processing technologies should not exceed the land available for energy production, L^{en} , as shown in Equation (27).

$$\sum_{s \in S} \sum_{r \in R} \sum_{x \in X} L_x M_{r,x,s} \leq L^{en} \quad (27)$$

L_x is the land use per unit raw material for energy source x and $M_{r,x,s}$ is the amount of raw material r for energy source x in season s .

5) Heat integration constraints

Low temperature waste heat from food and energy production processes as a potential energy source was considered. The constraints governing the use of waste heat for energy integration are as follows:

a) Heat exchange between waste heat and heat sink

The amount of heat exchanged between the waste heat source x' and energy sink y , $H_{x',y,s}$, is constrained by Equation (28).

$$H_{x',y,s} \leq H^{Max} z_{x',y,s} \quad \forall x' \in X', y \in Y, s \in S \quad (28)$$

$z_{x',y,s}$ is a binary variable to denote whether or not heat integration is included; the presence of this variable renders the energy model as a mixed-integer linear program (MILP). H^{Max} is the maximum heat load in the waste heat source for the gradient between inlet and outlet temperature, which ensures that Equation (28) always holds true.

b) Temperature difference constraint on the hot side

It is assumed that waste heat is exchanged through a counter current flow heat exchanger. A minimum temperature difference TD between the inlet temperature of the hot flow from the energy source x' , $T_{x'}^{in}$ and the temperature required by the heat sink y , T_y^{out} is required to

prevent temperature crossing in the heat exchanger. This constraint is given in Equation (29).

$$TD \leq (T_x^{in} - T_y^{out}) + M(1 - b_{x',y,s}) \quad \forall x' \in X', y \in Y, s \in S \quad (29)$$

M is the upper bound for temperature difference; it should be high enough to make the constraint holds with any value of the binary variable.

c) Temperature difference on the cold side

The same constraint applies for the minimum temperature difference TD between the outlet temperature of the heat source after exchange $T_{x'}^{out}$ and the temperature of the heat sink before exchange T_y^{in} as given in Equation (30).

$$TD \leq (T_{x'}^{out} - T_y^{in}) + M(1 - b_{x',y,s}) \quad \forall x' \in X', y \in Y, s \in S \quad (30)$$

d) Heat load availability of waste flows

The heat load $Q_{x',y,s}$, representing the amount of heat energy that can be transferred from the waste heat source x' to the heat sink y is given in Equation (31).

$$\sum_{y \in Y} Q_{x',y,s} = (T_{x'}^{in} - T_{x'}^{out}) CP_{x',s} t \quad \forall x' \in X', s \in S \quad (31)$$

$CP_{x',s}$ is the heat capacity flow rate of waste heat source x' for season s and t is the time period over which heat is transferred.

e) Heat load required by heat sinks

The heat load constraint required for the heat sink y is given in Equation (32).

$$\sum_{x \in X} Q_{x',y,s} = (T_y^{out} - T_y^{in}) CS_{y,s} t \quad \forall y \in Y, \forall s \in S \quad (32)$$

$CS_{y,s}$ is the heat capacity flow rate of the heat sink y for season s .

6) Electricity production

The total electricity produced from each source x can be determined through Equation (33).

$$\sum_{y \in Y} E_{x,y,s} = \sum_{r \in R} \eta_{x,r}^{el} M_{r,x,s} \quad \forall x \in X, s \in S \quad (33)$$

$\eta_{x,r}^{el}$ is the electrical conversion of source x for raw material r .

7) Heat production

The total heat generated from each source x can be determined through Equation (34),

$$\sum_{y \in Y} H_{x,y,s} = \sum_{r \in R} \eta_{x,r}^{he} M_{r,x,s} \quad \forall x \in X, s \in S \quad (34)$$

where $\eta_{x,r}^{he}$ is the heat conversion of source x for raw material r .

8) Surplus electricity

With technologies such as the co-generation of heat and power (CHP), it is reasonable to assume the design of the energy system will seek to meet the local heat demand, hence possibly leading to surplus electricity for export to grid. This surplus in each season s , $E_{x,grid,s}$, can be determined through Equation (35). As the benefit of avoiding the cumulative exergy consumption associated with grid electricity through local power export is included in the objective function, there is an incentive for the model to choose options which will export.

$$\sum_{x \in X} E_{x,grid,s} = \sum_{r \in R} \sum_{x \in X} \eta_{x,r}^{el} M_{r,x,s} - \sum_{y \in Y} \sum_{x \in X} E_{x,y,s} \quad \forall s \in S \quad (35)$$

3.3 Mathematical formulation for the simultaneous design

The simultaneous model will include all the constraint equations from section 3.2. In addition, since the three subsystems are now to be designed simultaneously, certain known parameters in the preliminary design analysis now become variables. Specifically, the electricity demand of food and water sinks in Equation (24), heat demand of food and water sinks in Equation (25), heat flow of waste heat sources in Equation (30), heat demand of food and water sinks in Equation (32) and water demand of food and energy sinks in Equation (18) are variables instead of known parameters.

3.3.1 Objective function

The optimisation problem for the simultaneous design is to minimise the total net cumulative exergy consumption for meeting the local food, water and energy demands, as formulated in Equation (36).

Minimise objective function:

Total net cumulative exergy resource consumption (NEC) = Total cumulative exergy consumption for food subsystem (TEF) + total cumulative exergy consumption for water subsystem (TEW) + total cumulative exergy consumption for energy subsystem (TEE) (36)

$$TEF = \sum_{s \in S} \sum_{d \in D} e_d^{imp} F_{d,s}^{imp} + \sum_{s \in S} \sum_{j \in J} \sum_{i \in I} e_{i,j}^{imp} N_{i,j,s}^{imp} + \sum_{s \in S} \sum_{j \in J} \sum_{o \in O} e_{o,j} U_{o,j,s}^{imp} + \sum_{c \in C} CA_c + \sum_{s \in S} \sum_{c \in C} OP_{c,s} \quad (37)$$

Equation (37) is similar to Equation (1) but in this case all the imported flows are from outside the boundary of the whole system.

$$TEW = \sum_{s \in S} \sum_{b \in B} \sum_{a \in A} (e^{ie} + e^{cw}) W_{a,b,s} + CA^{rw} \quad (38)$$

Equation (38) is similar to Equation (14) but where e^{ie} is the specific cumulative exergy of imported energy.

$$\begin{aligned} \text{TEE} = & \sum_{s \in S} \sum_{r \in R} e_r M_{r,s} + \sum_{s \in S} \sum_{y \in Y} \sum_{x \in X} e^{iel} E_{x,y,s} + \sum_{s \in S} \sum_{y \in Y} \sum_{x \in X} e^{ihe} H_{x,y,s} \\ & - \sum_{s \in S} \sum_{x \in X} e^{grid} E_{x,grid,s} \quad (39) \end{aligned}$$

Equation (39) is similar to Equation (23) with e^{iel} and e^{ihe} being the specific cumulative exergy of imported resources for producing electricity and heat, respectively and e_r is the specific cumulative exergy of only the imported raw material to the whole system.

3.3.2 Cross-subsystem flows

All the exchanges of flow occurring between the three subsystems and shown previously on Figure 7 need to be represented in the simultaneous model.

1) Water requirements

The water requirements for producing food d , W_s^{FD} , can be determined by Equation (40).

$$W_s^{FD} = \sum_{d \in D} (WC_d + WP_d) F_{d,s}^{local} \quad \forall s \in S \quad (40)$$

where WC_d and WP_d are the amount of water required for agriculture and industrial processing, respectively, per unit of produced food d .

The water requirement for producing energy e , W_s^{EN} , is determined by Equation (41):

$$W_s^{EN} = WE \sum_{s \in S} \sum_{y \in Y} \sum_{x \in X} E_{x,y,s} \quad (41)$$

with WE being the amount of water required per amount of energy produced and $E_{x,y,s}$ the amount of energy from source x to sink y in season s .

2) Wastewater generation

The wastewater generation from the food subsystem, WG_s^{FD} , in season s was determined by Equation (42):

$$WG_s^{FD} = \sum_{d \in D} WGP_d F_{d,s}^{local} \quad \forall s \in S \quad (42)$$

where WGP_d is the amount of wastewater generated per unit of produced food d .

Equation (43) determines wastewater generated from the energy production processes, WG_s^{EN} :

$$WG_s^{EN} = WEG \sum_{s \in S} \sum_{y \in Y} \sum_{x \in X} E_{x,y,s} \quad (43)$$

with WEG being the amount of wastewater generated per unit energy produced.

3) Energy demand

The electricity demand for the food subsystem ELD_s^{FD} is determined through Equation (44):

$$ELD_s^{FD} = \sum_{d \in D} ELD_d F_{d,s}^{local} \quad \forall s \in S \quad (44)$$

where ELD_d is the electricity demand per unit of food d .

The heat demand for the food subsystem, HED_s^{FD} is determined through Equation (45)

$$HED_s^{FD} = \sum_{d \in D} HED_d F_{d,s}^{local} \quad \forall s \in S \quad (45)$$

where HED_d is the heat demand per unit of food d .

The electricity demand for the water subsystem, ELD_s^{WA} is determined through Equation (46):

$$ELD_s^{WA} = SED^{WA} \sum_{d \in D} WGP_d F_{d,s}^{local} \quad \forall s \in S \quad (46)$$

where SED^{WA} is the electricity demand for treating unit wastewater.

The heat demand for the water subsystem, HED_s^{WA} , is determined through Equation (47)

$$HED_s^{WA} = SHD^{WA} \sum_{d \in D} WGP_d F_{d,s}^{local} \quad \forall s \in S \quad (47)$$

where SHD^{WA} is the heat demand for treating unit wastewater.

The heat capacity flow rate of waste heat sources satisfies Equation (48), which is based on Equation (31).

$$CP_{x',s} = \frac{Q_{x',y,s}}{(T_{x'}^{in} - T_{x'}^{out})} \quad (48)$$

Where heat integration occurs, it is assumed that heat removed from the hot flows (i.e. waste heat sources) equals the heat gained by the cold flows (i.e. heat sinks). Thus, the heat capacity flow rate of the cold flows can be determined by Equation (49) based on Equation (32).

$$CW_{y,s} = \frac{Q_{x',y,s}}{(T_y^{out} - T_y^{in})} \quad (49)$$

4 Case study

The methodology for the design of local production systems is illustrated by a case study for the integrated design of the food-energy-water nexus in Whitehill and Bordon, an area identified for the development of an eco-town in the UK. The specificities of this eco-town are given in Table 1 and are based primarily from data given in the master plans for the eco-town (Whitehill and Bordon, 2012) and DEFRA (2014). For simplicity, a small selection of foods typically consumed and with potential for local production was chosen. The land availability for energy production includes land that can be used for solar and wind power generation and the installation of CHP plants. It excludes land for biomass sources as these areas are already part of the fixed geographical setting and are not to be optimised. All data used in the design can be found in the supporting document.

The objective is to select the food, energy and water production processes and to determine the flow rates of source flows to sinks that will minimise total resource consumption while observing a set of local ecological and technical constraints for satisfying local demands for food, energy and water.

The exergy content of flows from Type-II processes was not considered as it is assumed that they do not have alternative competing uses in this case study. Flows from Type-I processes were accounted by their cumulative exergy consumption as normal. Note that wheat can be planted either in autumn or spring but harvested in late summer (UK Agriculture, 2014a) while potatoes are harvested in summer and autumn in UK (UK Agriculture, 2014b).

The models were solved using GAMS (Rosenthal, 2015), with CPLEX as the mixed-integer linear model solver and BARON as the mixed-integer nonlinear model solver.

Table 1: Specificities of Whitehill-Bordon eco-town

Specificities	Value
Population	17,000
Agricultural land	17 ha
Groundwater abstraction limit	14,875,942 t/y
Residential water demand	887,081 t/y
Residential electricity demand	90,254 t/y
Land availability for energy production	70 ha
Rainwater availability (t/y)	
Winter	255,091
Spring	209,793
Summer	209,793
Autumn	273,312
Residential heat demand (GJ/y)	
Winter	112,128
Spring	85,848
Summer	82,344
Autumn	96,360
Food demand (t/y)	
Bread	224
Potato	403
Pork	46
Beef	88
Availability of energy sources (PJ/y)	
Wood chips	1.66
Organic waste (Animal manure and food waste)	0.10
Wind	0.40
Solar	15.8 GJ/y/m ²

4.1 Preliminary design analysis: illustration with the food production subsystem

The individual food, water and energy models were solved separately. Scenario analysis was performed for each subsystem to analyse the impacts on the decision variables of variations in demand and CExC of inputs due to different energy or water source options. This section presents the investigation on the food production subsystem, to illustrate the learning that could be gained from the preliminary design analysis. Detailed results of the water and the energy production subsystems are included in the supporting document.

Five scenarios were analysed for the food subsystem as summarised in Table 2. Scenario F1 investigates the impact of using conventional energy and water sources for the local food production subsystem. Scenarios F2 and F3 respectively analyse the impact of supplying all the energy demands for food production from wood chip CHP and from organic waste CHP respectively. Scenario F4 is similar to F2 but additionally investigates the impact of supplying its water demand by a different water source namely collected rainwater for crop cultivation and the rest of water demand by groundwater. It is assumed that there is enough collected rainwater available for crop cultivation with no CExC associated with it. Scenario F5 uses organic waste CHP and rainwater for crop cultivation.

As compared to F1, the specific CExC of electricity decreases by 10.6% and that of heat by 2% in F2. The decrease in specific CExC of heat and electricity from F1 to F2 did not affect the result of the food subsystem design. However, the more substantial decrease in specific CExC of electricity by 86% and 63% heat from F1 to F3 led to significant changes to the result of the food design as 100% of potatoes and 28% of bread demand are satisfied locally in F3 compared to 75% potatoes and 36% bread demand in F1. More specifically, Table 2 shows that from F2 to F3 more electricity is used but less heat and water is consumed. Figure 8 illustrates that, as the CExC of electricity is reduced in F3, water becomes more important for potato production. From Table 2, electricity consumption decreases when only bread is produced. This means potato production was more dependent on this input due to the relatively high electricity demand required for potato storage. In F4, lower CExC water resource (rainwater) combined with high CExC energy source (and potato production being much more dependent on electricity), changes the design to the production of bread only, despite that this design requires higher heat, water and fertiliser consumption. From these insights, it is not surprising that in F5, with low CExC water and energy sources, bread production is also the only locally produced food.

Table 2: Preliminary design analysis for food production system

Proposed design	Scenario				
	F1	F2	F3	F4	F5
Energy source	CExC of grid electricity = 5.97 MJ exergy/MJ electricity CExC of natural gas heat from boiler = 2.05 MJ exergy/MJ heat	Electricity from biomass CHP, CExC = 5.34 MJ exergy/MJ electricity Heat from biomass CHP, CExC = 2.01 MJ exergy/MJ heat	Electricity from organic waste CHP, CExC = 0.83 MJ exergy/MJ electricity Heat from organic waste CHP, CExC = 0.76 MJ exergy/MJ heat	Electricity from biomass CHP, CExC = 5.34 MJ exergy/MJ electricity Heat from biomass CHP, CExC = 2.01 MJ exergy/MJ heat	Electricity from organic waste CHP, CExC = 0.83 MJ exergy/MJ electricity Heat from organic waste CHP, CExC = 0.76 MJ exergy/MJ heat
Water source	CExC of groundwater = 0.06 MJ/kg	CExC of groundwater = 0.06 MJ/kg	CExC of groundwater = 0.06 MJ/kg	CExC of groundwater = 0.06 MJ/kg CExC of untreated rainwater = 0 MJ/kg	CExC of groundwater = 0.06 MJ/kg CExC of untreated rainwater = 0 MJ/kg
Total electricity consumption (GJ energy/y)	73.8	73.8	81.1	52	52
Total heat consumption (GJ energy/y)	81.2	81.2	63.5	134	134
Total water consumption (t/y)	194,726	194,726	156,374	309,784	309,784
Total imported fertilisers (t/y)	3.35	3.35	3.29	3.53	3.53
% food demand satisfied locally					
Potatoes	75	75	100	0	0
Bread	36	36	28	60	60
Pork	0	0	0	0	0
Beef	0	0	0	0	0
Total CExC (GJ/y)	135,260	135,168	134,247	130,283	129,747

In summary, the adoption of energy and water sources with relatively high CExC produces a design of mixed food production with potatoes being favoured. In contrast, either high or low CExC energy source combined with relatively low CExC water source favours bread production. Note that this is also because assuming a value of CExC equal to zero for rainwater favours water intensive bread production.

This example illustrates how the interactions between subsystems can be systematically analysed in order to obtain insights which are not intuitively obvious, hence demonstrating the value of the preliminary design analysis.

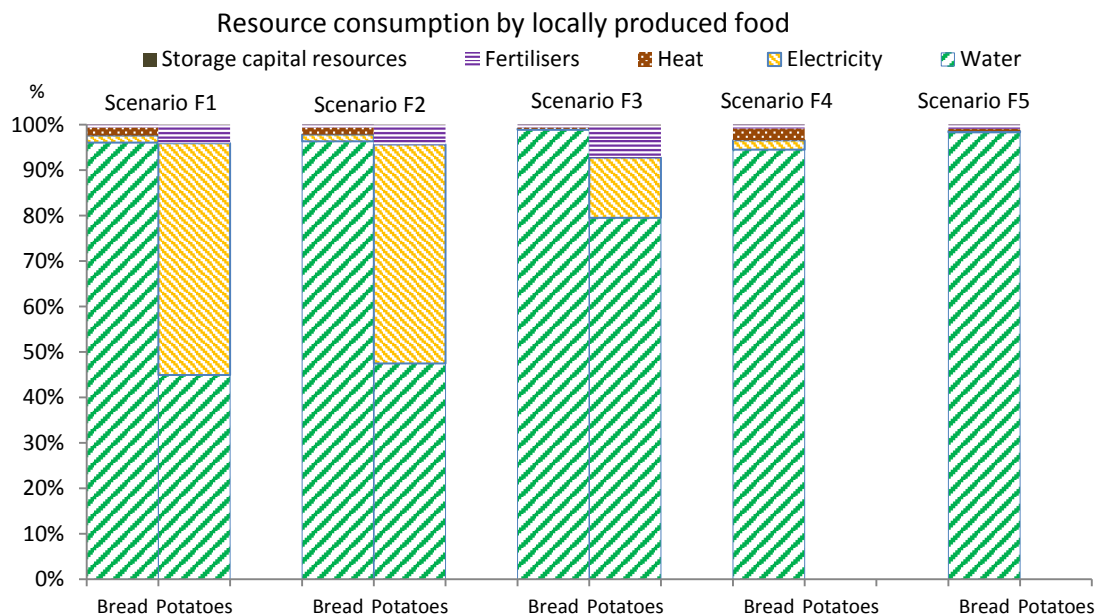


Figure 8: Contribution analysis of resource consumption for each locally produced food

4.2 Simultaneous design

The results of the simultaneous optimisation for a design period of one year are illustrated in Figure 9 and reported in Table 3.

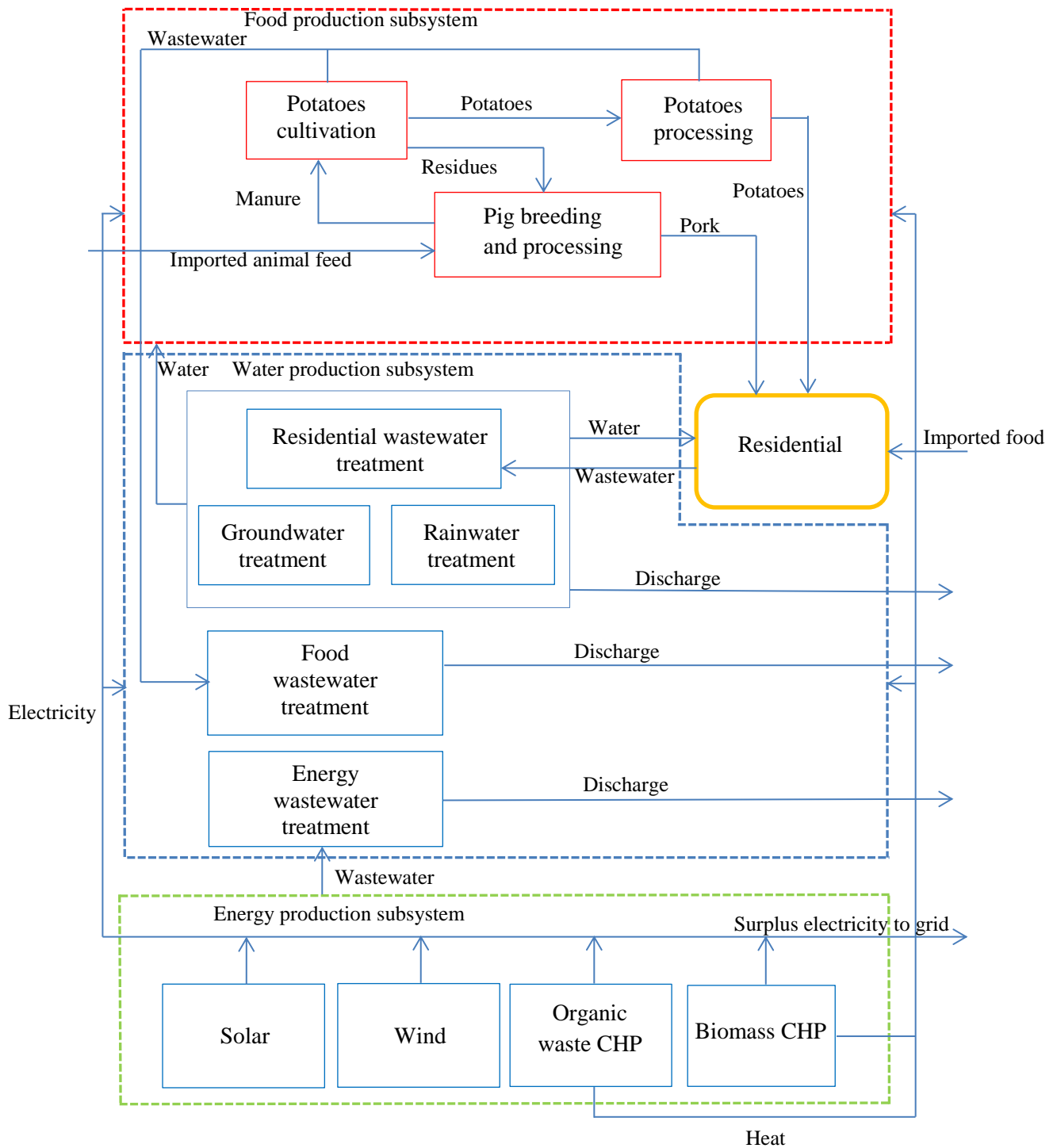


Figure 9: Results of simultaneous design

Table 3: Detailed results from simultaneous design

Source	Sink	Locally produced food (t)			
		Winter	Spring	Summer	Autumn
Local pork	Local consumption	10	10	10	10
Local potatoes	Local consumption	0	0	36	36
Imported animal feed	Pig rearing	9	9	0	0
Potato residues	Pig rearing	0	0	9	9
Pig manure	Potato cultivation	0	0	0.14	0.14
Source	Sink	Water supply (t)			
		Winter	Spring	Summer	Autumn
Water flows @ ≤0.010 g COD/kg Groundwater: 50.1% Rainwater: 35.9% Treated residential wastewater: 14.0%	Residential	586,867	586,867	586,867	586,867
	Food processes (cultivation and processing)	59,552	59,552	60,403	60,403
	Energy processes	5257	4031	3868	4522
Water flows @ ≤0.10 g COD/kg	Discharge	276,475	278,727	278,162	276,794
Source	Sink	Energy supply (GJ)			
		Winter	Spring	Summer	Autumn
Electricity Biomass CHP: 23.5% Wind: 40.6% Solar: 35.9%	Water processes	7685	7992	7966	8011
	Residential	22,566	22,566	22,566	22,566
	Food processes	15.9	15.9	30.5	30.5
	Grid (export of surplus electricity)	18,757	22,484	29,767	34,136
Heat from biomass CHP	Residential	82,161	60,199	57,270	68,392
Heat from biomass CHP	Water processes	0.03	0.03	0	605
Heat from organic waste CHP	Residential	11,463	11,436	12,045	12,045
Heat from organic waste CHP	Food processes	0	14.9	0	0
Heat from organic waste CHP	Water processes	582	594	0.17	0
LT waste heat from biomass CHP	Residential	16,095	11,804	11,229	13,514
LT waste heat from biomass CHP	Food processes	14.9	0	0	14.9
LT waste heat from organic waste CHP	Residential	2409	2409	1800	2409
LT waste heat from organic waste CHP	Water processes	0	0	594	0
LT waste heat from organic waste CHP	Food processes	0	0	14.9	0

The total CExC was determined to be 273,901GJ/y. Though bread and potatoes were produced in the food scenarios of the preliminary analysis of the food subsystem, the simultaneous design indicates that 17.6% of potatoes and 86% of pork demand can be satisfied locally; suggesting that pork will offer better compromise on resource consumption for the overall food-energy-water local design. For water supply, about 14% treated residential wastewater, 50% groundwater and 36% rainwater would be used to meet the water demand of the eco-town. The eco-town is also self-sufficient in its electricity and heat supplies through the use of locally available resources of organic waste, wood chips, solar and wind, and with waste heat recovery providing for 16.4% of its heat demand.

In order to fully investigate the benefits of the simultaneous integrated design of the local system, two further reference scenarios were developed and compared with the integrated design. The first scenario, termed “centralised supply”, assumed that all the local demands of the eco-town were met by imported food and conventional utility sources of grid electricity, heat from natural gas boilers and groundwater. The second scenario, termed “design in silos” involves designing each subsystem separately and independently without considering the synergies between them. The food subsystem is designed considering only grid electricity and heat from natural gas boilers; groundwater and any wastewater generated is treated within the food subsystem. The water subsystem is designed to supply the water demand of the residential sector. It considered only the options for using water sources of different quality available within this subsystem, such as rainwater and treated residential wastewater (i.e. COD concentration). In addition, the energy subsystem is also designed to only meet the residential energy demand, without considering heat recovery options between the subsystems but allowing for choice from the full range of energy sources.

A comparison of the net CExC of all three scenarios for food, water and energy subsystems is given in Figure 10. There is a general decrease in the CExC of the food, water and energy

subsystems of the integrated design as compared to the other two scenarios. Overall, the total CExC of the centralised supply and that of design in silos were determined to be about 6 and 2 times respectively higher than the integrated design. Figure 11 indicates that there is not much difference in the resource consumption of the food subsystem for the three scenarios. Though imported food dominates resource consumption in the food subsystem, producing food locally consumes high volumes of water which reinforces the need to exploit water re-use between the subsystems for local food production. Interestingly, imported fertilisers account for only a negligible percentage of total CExC in all three scenarios; suggesting that for this particular case study coupling between the subsystems (e.g. re-use of organic residues from water and energy processes) for satisfying nutrient demands, not considered in this study, will have a negligible impact on the total resource consumption of the food subsystem.

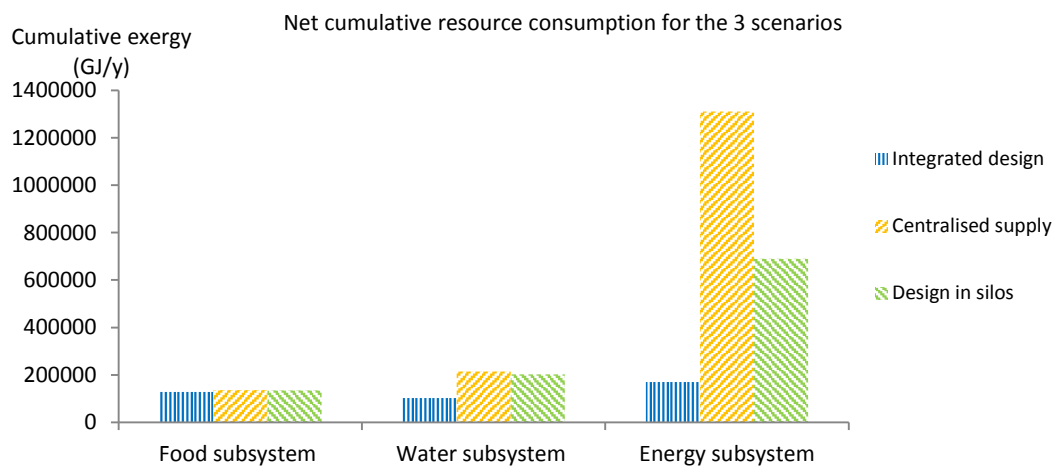


Figure 10: Net resource consumption for each scenario

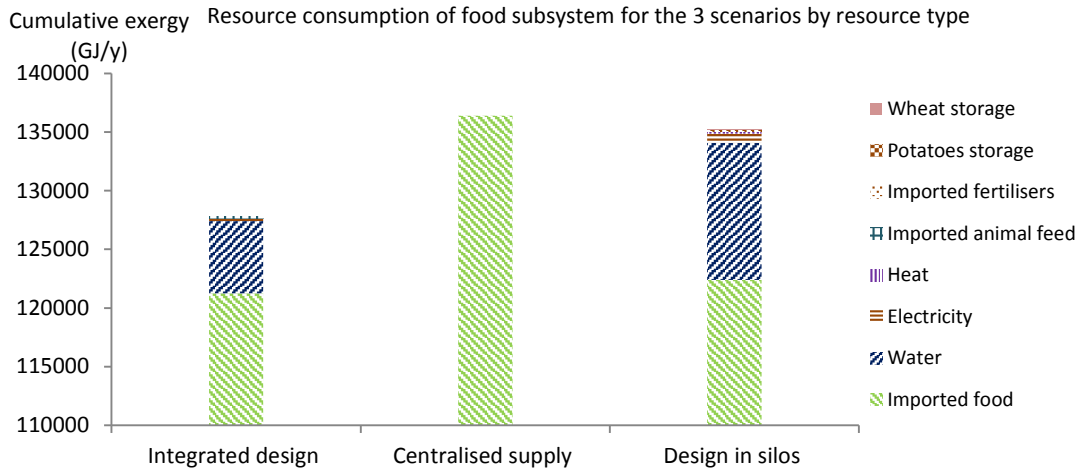
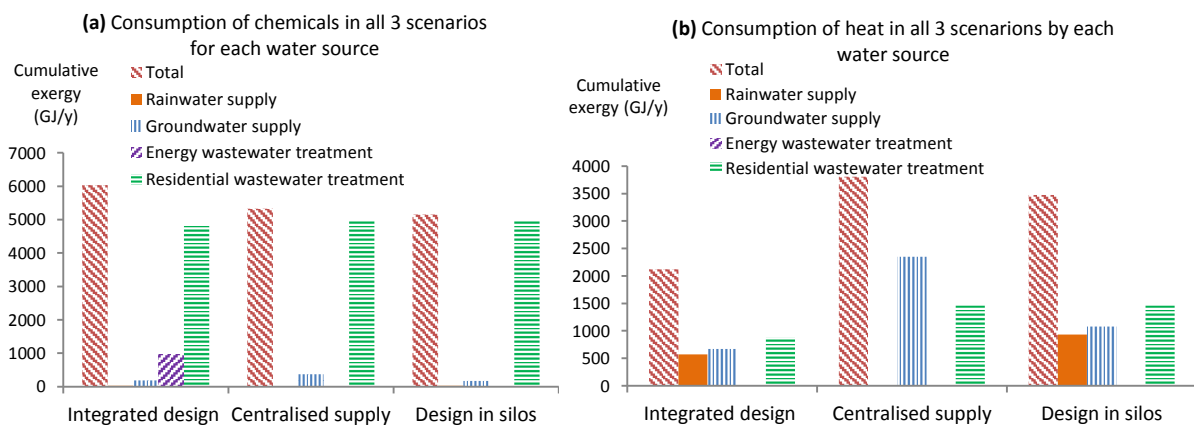


Figure 11: Cumulative exergy of food subsystem for all 3 subsystems

In addition, the CExC of all the resources associated with each water source in all scenarios is analysed in Figures 12(a)-(d). The CExC of chemicals for wastewater treatment was higher for the integrated design due to higher volumes of wastewater generated from the food and energy subsystems. Both the integrated and design in silos scenarios require capital resources for rainwater storage as compared to the centralised supply scenario.



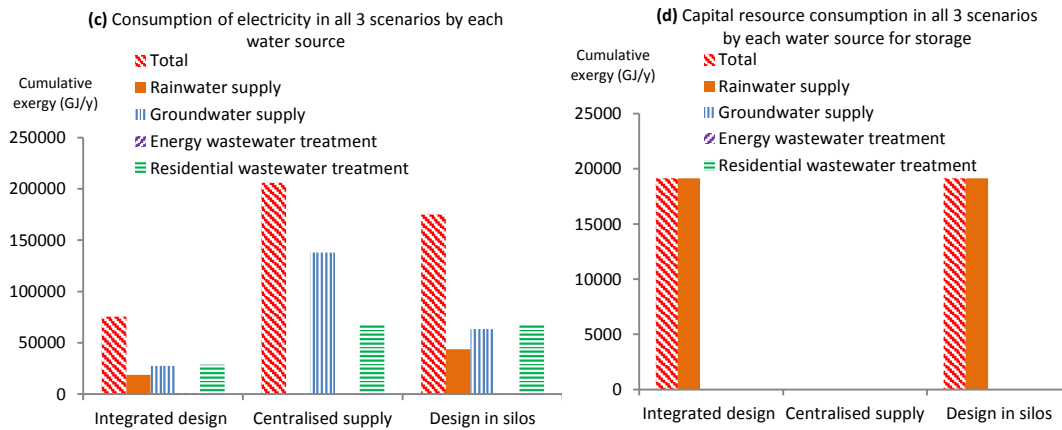


Figure 12: Cumulative consumption of resources (a) chemicals, (b) heat, (c) electricity, (d) capital resources by all 3 scenarios for each water source

However, the higher CExC for chemicals (cf. Figure 12a) and rainwater storage (cf. Figure 12d) in the integrated design is offset by much less resource intensive energy consumption (cf. Figures 12b and 12c). As compared to the centralised supply and design in silos scenarios which consume conventional energy for their water subsystems, solar, wind, wood chip and organic waste CHP as well as low temperature waste heat generated from the energy subsystem are used to satisfy the energy demands of the water subsystem of the integrated design. Figure 12c also indicates that using rainwater to satisfy part of the water demand in the eco-town, as is the case in the integrated design and design in silo scenarios, will also contribute to lower total resource consumption as it has very low CExC as compared to groundwater supply. Besides, the CExC associated with groundwater (cf. Figures 12a-c) is not insignificant; re-using part of the treated residential wastewater instead of discharging them to the local environment will reduce the consumption of fresh water resource and contribute to lower total resource consumption.

Figure 13 illustrates the CExC for production of electricity, heat and surplus electricity in all three scenarios by each energy source (i.e. natural gas boiler, wood chips CHP, organic waste CHP, grid, solar and wind power). The major improvement in resource consumption of the

energy subsystem in the integrated design as compared to the centralised supply is due to the significantly lower CExC associated with solar, wind and organic waste CHP than that of grid electricity and natural gas boilers. For the design in silos, the resource available for organic waste CHP is constrained to be from the residential sector alone, and the renewable energy options are not required, with the majority of demand met by biomass CHP. The integrated design allows use of organic wastes from the food and water sectors as well, and also allows more than 16% of the heat demand in water and food sub systems to be met by low temperature waste heat recovered from the energy subsystem. The total surplus electricity generated from the integrated design is higher by about 60% as compared to that of the design in silos, further contributing to a lower overall net CExC.

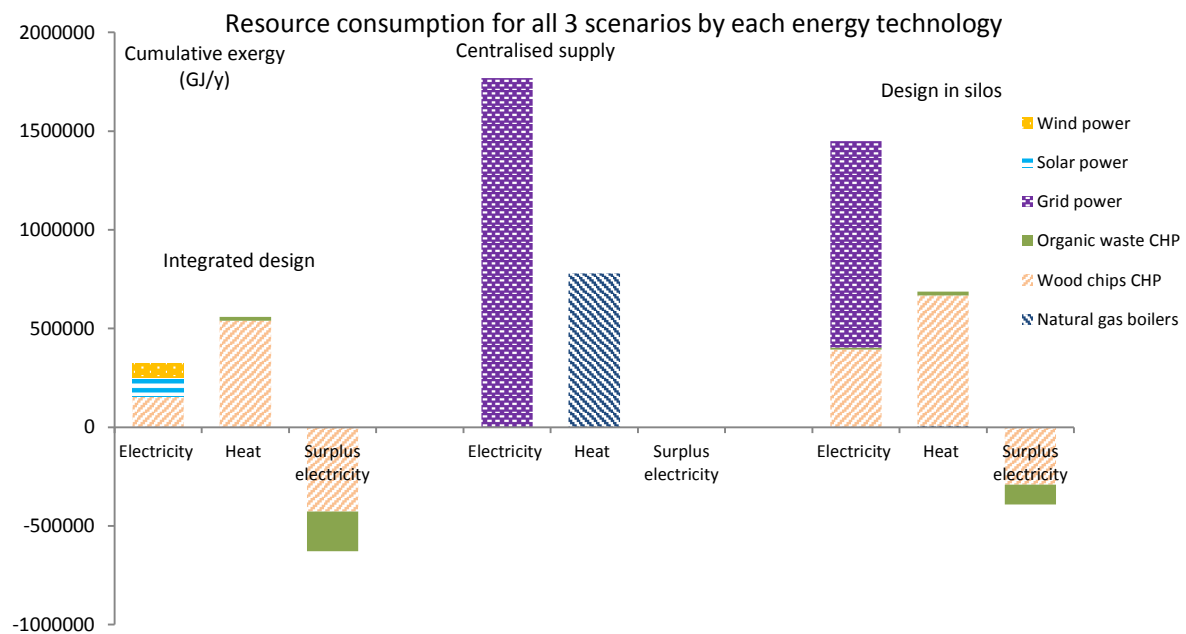


Figure 13: Cumulative consumption by each technology for energy production in all scenarios

5 Conclusions

This work has proposed a methodology for the design of local production systems, and developed a superstructure-based optimisation model specifically for design of the food-

energy-water nexus in a local context. The application of the methodology and the mathematical model to a design problem for satisfying local demands in a UK eco-town has shown that the proposed approach can produce superior results.

Based on the optimisation models of individual subsystems, the preliminary design analysis allows insights to be gained about the design alternatives. It reveals interdependencies between subsystems and how the inter-subsystem coupling options would affect substantially the choice made for the internal design of individual subsystems. The simultaneous approach, utilising models of all subsystems and accounting for all the possible interactions between the subsystems, offers an optimal solution for the integrated, whole-system design. It was shown that co-designing the subsystems of the food-energy-water nexus allows capture of all the integration options and exploitation of emerging synergies and opportunities for circularity. These include the exchange of waste heat, treated domestic wastewater and rainwater between subsystems and the re-use of organic residues between different processes, with significant overall benefits in terms of the reduction of total resource consumption as compared to importing all resources to satisfy local demands and to designing the individual subsystems in isolation from one another. About 50% resource savings were achieved by the integrated design of the local food-energy-water nexus as compared to the design in silos approach, which is in line with the reported benefits by integrated design as applied to other systems, e.g. 29% reduction in total cost with material by-products exchange (Cimren et al., 2010) and more than 80% savings in total energy cost with the implementation of waste heat recovery in industrial parks (Chae et al., 2010).

The work presented in this study only focuses on designing a local production system from scratch. On-going work is investigating the adaptation of the approach for retrofitting existing systems. The present work has directed optimisation to the minimisation of resource intensity measured by cumulative exergy consumption, although the modelling approach to capturing

the interconnections between different processes and subsystems may be applied to other objective functions desired by the concerned stakeholders. Furthermore, the focus on local systems, addressing the need for systematic support to the emerging initiatives in sustainable production at the local scale, would mean “local” optimality in resource allocation which theoretically may imply global sub-optimum when the resource consumption for production is measured at the global scale. On the other hand, practical limitations such as availability of data and feasibility of implementing an optimal solution may prevent optimisation of a nature similar to that presented in this work from being meaningful at a much larger scale. This dilemma needs to be better understood and addressed in future work.

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