A framework for modelling local production systems with techno-ecological interactions

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Nomenclature

A_h	Harvested heathland area
B	Standing biomass
$C_{(s+b)}$	Total carbon capture rate
C_{soil}	Carbon stock in soil
D_e	Demand of reference
F	Flow
$f_{AG,s}$	Fraction of biomass growth allocated to above-ground biomass of species *s*
F_{cons}	Resource consumption rates of processes
f_{cut}	Annual cut fraction
F_{dep}^{N}	Atmospheric nitrogen deposition
F_e	Energy supplied from bioenergy production system
F_{el}	Net electricity production
F_{gen}	Resource generation rates of processes
$F_{growth,s}$	Biomass growth rate of species *s*
$F_{harv,s}$	Harvest rate of species *s*
F_{in}	Input flows to system
${F_{in}}^{ep,b}$	Input biomass flow to energy production
${F_{in}}^{h,f}$	Input fertilizer flow to heathland
${F_{in}}^{i,j}$	j^{th} inlet flow of component *i*
F_{out}	Output flows from system

$F_{out}^{ep,f}$	Outlet fertilizer flow from energy production
$F_{out}^{h,b}$	Outlet biomass flow from heathland
$F_{out}^{k,m}$	m^{th} outlet flow of component *k*
$F_{mort,s}$	Mortality or litter production rate of the species *s*
F_p	Generation or consumption rates of processes
H_{biogas}	Heating value of biogas
H_{wb}	Heating value of woody biomass
HP	Human Population
I_s	State indicator
I_f	Flow indicator
I_{sf}	State-flow indicator
k	Growth rate constant
k_{biogas}	Biogas yield from input biomass flow
k_{lossC}	Soil C loss rate constant
$k_{m,s}$	Mortality or litter production rate constant of species *s*
k_p	Process rate constant
L	Competition function of the Lotka-Volterrra form
M_s	Mortality rate of species *s*
N	Nitrogen
S	State variable
s1	Heather
s2	Grass
t	Time
y_C	Carbon fraction in biomass
$y_{N,s}$	Nitrogen content in biomass of species *s*
$y_{soft,s}$	Soft fraction in biomass from species *s*
η_{el}^{biogas}	Electricity efficiency of CHP plant using biogas
η_{el}^{wb}	Electrical efficiency of CHP using woody biomass
δ_e	Demand satisfaction indicator

Keywords

localized production, techno-ecological system, bioenergy, modelling, symbiosis

<heading level 1> Summary

At the local scale, interconnected production, consumption, waste management and other man-made technological components interact with local ecosystem components to form a local production system. The purpose of this work is to develop a framework for the conceptual characterization and mathematical modelling of a local production system to support the assessment of process and component options that potentially create symbiosis between industry and ecosystem. This framework has been applied to a case study to assess options for the establishment of a local energy production system that involves a heathland ecosystem, bioenergy production and wastewater treatment. We found that the framework is useful to analyze the two-way interactions between these components in order to obtain insight into the behavior and performance of the bioenergy production system. In particular, the framework enables exploring the levels of the ecosystem states that allow continuous provisioning of resources in order to establish a sustainable techno-ecological system.

<**heading level 1**> **Introduction**

The increasing world population and the subsequent rise in energy and materials consumption are leading to resource constraints. At the same time, ecosystem functions are being affected due to the release of pollutants by human activities, threatening the continuous supply of ecosystem goods and services (MEA 2005). This drives the need for considering new ways to meet human needs in a more sustainable manner. One possible pathway is to shift the supply of basic human needs from large scale centralized production systems to localized production systems. Localized production creates opportunities to integrate ecosystem and technological components to satisfy the needs of the local population whilst observing the local environmental constraints, and to foster symbiosis between different processes.

Localized production as a means to achieve sustainability has been considered as part of alternative forms of economic development (Curtis 2003; Johansson et al. 2005). The UK's Royal Academy of Engineering identifies the positive potential for localized energy and water supply particularly with respect to resilience in the context of climate change adaptation (RAE 2011). This is also in line with the Millennium Ecosystem Assessment that shows that the "adapting mosaic" scenario is the only one in which the state of all ecosystem services is expected to be enhanced by focusing on local management strategies (MEA 2005).

Localized production is closely related to existing work in industrial ecology. Under the broad theme of industrial symbiosis (Chertow and Ehrenfeld 2012), supply of water (Liang et al. 2011) and energy (Hiete et al. 2012) and waste treatment (Eckelman et al. 2014) have been studied for eco-industrial parks. Desrochers (2001) has analyzed the exchange of wastes, by-products and energy among closely situated firms and the incentives that promote linkages at both the local and interregional levels. Fröhling et al. (2013) have proposed a material-flow based approach for the analysis of the connections between production and recycling networks. Studies on industrial ecosystems using network theory suggest that higher structural cyclicity has the potential for a higher maximum thermal efficiency (Layton et al. 2012) and that increasing connectance between components might lead to higher resource efficiency yet possibly at the expense of stability and environmental performance (Hardy and Graedel 2002). The reason for this might be that, although life cycle assessment (LCA) has been applied to study industrial symbioses (Mattila et al. 2012), connections and interactions with two important parts of the life cycle are often missing: 1) the ecosystem, as the ultimate resource provider, and 2) final consumption by population where resources are degraded to low quality. In particular, the importance of supporting decision making by considering techno-ecological interactions has been highlighted by several authors (Urban et al. 2010; Urban and Bakshi 2013; Song and Frostell 2012).

In this article, we present a methodological framework to study the links between local ecosystems, production and consumption components in order to devise ways to meet the needs of the local population whilst maintaining the ecosystem capacities that can keep the local production system operating in a sustainable manner. The framework consists of conceptual and mathematical characterization of a local system and is illustrated by a case study comprising a heathland ecosystem, sewage water treatment and bioenergy production.

<heading level 1> The concept of a localized production and consumption system

Within the wide spectrum of possible geographical scales for organizing production activities, the term “local” is undoubtedly relative. Nevertheless, it generally holds that the scope of a local system should be one which emphasizes the co-location of resource extraction, production and consumption and which enables the account of the affected ecosystems at a detailed level. This can often correspond to some of the existing, lower levels of public governance (e.g. a town, city, or county) where sustainability-embracing decisions may be pursued based on sufficient “local” details.

The general concept of localized production and consumption is represented in figure 1, consisting of (i) the natural environment and the associated ecological processes and (ii) the human-created components and the associated production and consumption processes, all within a specific geographical boundary. The basic needs of local population (nutrition, thermal comfort, hydration, etc.) are the drivers of a local production system. Such needs are met through energy and material flows (food, fuel, water) generated from the production processes. These production processes make use of locally available (often renewable) resources provided by ecological processes in the local environment. In turn, the production processes and consumption affect the local environment through the discharge of pollutants and wastes. External resources will be needed as incoming flows, as local environment cannot provide all the types and amount of resources, and some excess products (e.g. surplus electricity) or pollutants and wastes (e.g. CO_2 emissions) may be exported as outgoing flows. This diagram emphasizes that it is through the ecological, production and consumption processes that we try to satisfy the basic human needs. How to devise and study the wise integrations between them in a systematic way is addressed in this article by proposing and illustrating a conceptual and quantitative modelling framework.

From the perspective of industrial ecology, the present research envisages localized production activities in the form of a synergetic and evolving system in which heterogeneous production facilities are integrated to potentially achieve a high degree of resource efficiency and resilience, consequently enhancing the (collective) economic viability whilst maintaining harmony with the ecosystem. Besides, a local production system will interact with peers in neighboring localities with different sets of resource availability and population needs, and also exchange with centralized large-scale production and distribution infrastructures, which are either desirable elements in the appropriate economic balance between centralized and localized systems or merely legacies in the course of shifting towards localized production.

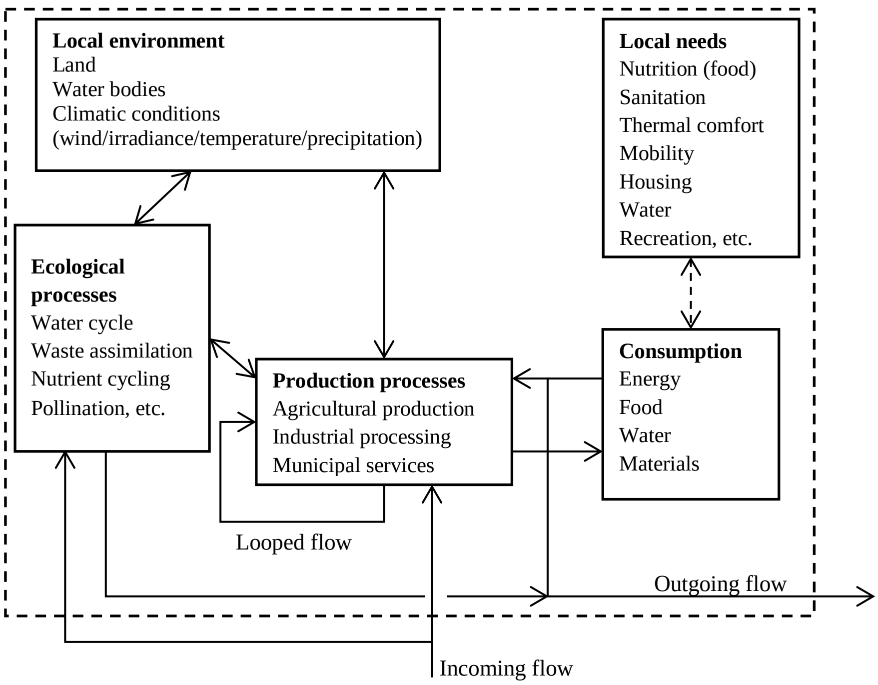


Figure 1. The concept of localized production, consumption and ecological processes.

<heading level 1> Conceptual characterization of local production systems

The first step is to provide a systematic and common conceptual framework. To this end, the various blocks and their interrelations in figure 1 can be represented as in figure 2, where the set of common concepts are linked through subclass (i.e. one concept is a subclass or special case of another concept), composition (i.e. an object depicted by one concept forms part of an object by another concept), or general association (e.g. a process *affects* a state or a flow rate). This conceptual model is proposed to facilitate the identification and characterization of key components and their connections, which may form a basis for further mathematical modelling among other possible uses. The conceptual depiction of the system is organized into different views, namely structural, behavioral, functional and performance. In addition, a physical view is needed to address the physical nature of components, flows, processes and states.

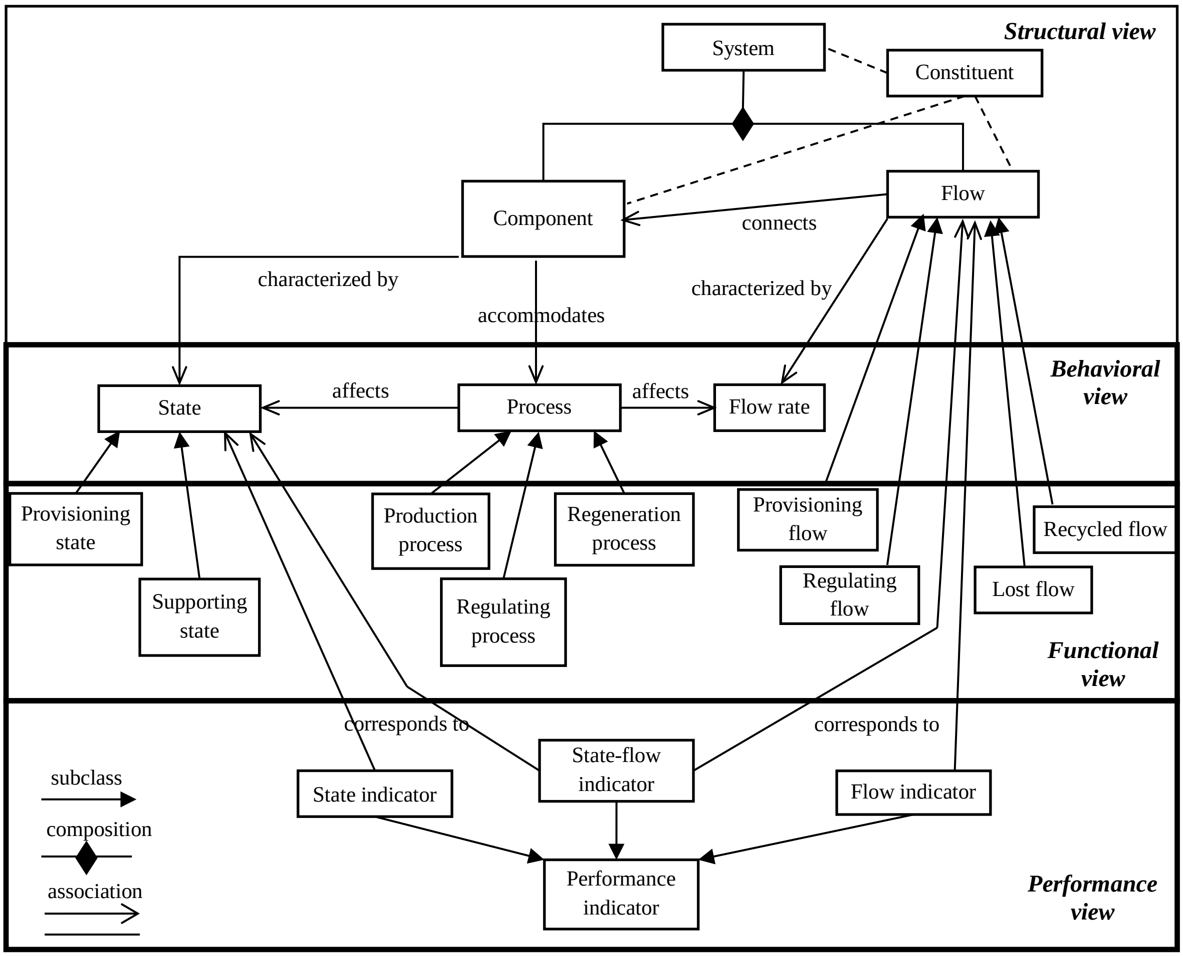


Figure 2. Conceptual model for characterization of localized production systems.

<heading level 2> Structural view

In the structural view, the system is composed of components and flows. A **component** is a subsystem, which is connected with other components via **flows**. The content of a component or a flow is represented by the concept of **constituent**, which describes the basic ingredients of the system. Depending on the physical nature of a component or a flow, its constituents could include certain type(s) of material, energy, physical objects, biological entities, etc. Components are characterized by states and host processes, as depicted below by the behavioral view. It generally holds that a system or a system component can be decomposed hierarchically (a component may be composed of several components and flows from a lower level).

<heading level 2> Behavioral view

Processes and states are the key concepts for depicting the behavior of a system. A **process** may change flows by varying their condition or nature. It may also modify the flow rates and the states of the components. The term **state** refers to the state variables that describe the attributes or conditions of the components. Thus, the behavior of the system is determined by the dynamics of the processes and the extent of the modifications on flow rates and states. By examining the processes, the current and future states of the components can be analyzed, and subsequently the ability or capacity of the system to maintain the provision services for meeting local needs within ecological constraints can be determined. The latter aspect is further unfolded by the functional view.

<heading level 2> Functional view

If one takes a human-centric, utilitarian view on top of the abstract concepts of a system's structure and behavior as presented above, a functional view can be introduced by further classifying states, processes and flows into subclasses according to their direct or indirect roles in providing products and services for meeting human demands, similar to the approach adopted by the MEA (2005) for classifying ecosystem services. Specifically, states can be classified into provisioning and supporting states. A **provisioning state** refers to the capacity of the system to meet a certain demand; for example, the wheat productivity of a farmed land (as the capacity for providing a flow of wheat) or the forest coverage of an area (as the capacity for meeting cultural/recreational needs). A **supporting state,** often manifested as a stock, is one required to maintain one or more provisioning states (for example, a certain level of soil depth or nutrient content required to maintain the level of wheat productivity). Due to the roles of the supporting states, these states may impose limits to a local production system. As the system is dynamic, it is important to assess the changes in these supporting states caused by processes and flows and the corresponding changes in the provisioning states which may be enhanced or reduced as the system evolves with time.

A similar functional classification can be made to the processes according to their roles in changing the flows and states. Here, processes are classified as production, regulating, and re-generation processes. Flows are classified as provisioning, regulating, recycled and lost flows. The **provisioning flows** meet the local needs for products or services and are produced by production processes. The **production processes** transform provisioning flows into other provisioning flows (of the same or different form, with the same or different constituents, from/to the same or different component) and into degraded flows. Degraded flows are a subclass of flow that be lost or appear as intermediate flows to be further processed by regeneration or regulating processes (e.g. wastewater treatment). **Regeneration processes** transform a degraded flow of constituents into a form that can be returned to the production processes as a **recycled flow**, or to a supporting state in the form of a stock. **Regulating processes** do not produce any direct provisioning flow but support the regeneration processes and the maintenance of supporting states. They act as buffering mechanisms in the system to alleviate any burden mainly imposed by the production processes and the resulting pollutant emissions. Regulating processes may generate flows necessary for regulation. Such flows are called **regulating flows** and examples include litter nutrients mineralized in soil or direct fertilizer application, as these are flows that can help to balance deficit of nutrients thus regulating crop yields. Emitted flows might damage the ecosystem if they are discharged at a flow rate that is higher than the assimilation rate of the regulating processes. Emitted flows could also be transported and exported to other systems and therefore can be classified as **lost flows** (this means lost by the local system, but might be gained by any other system).Other lost flows are those diverted by natural or technological components and transported outside of the local system boundary (e.g. rainwater discharged into a river).

<heading level 2> Performance view

The functioning of a local production system can be evaluated quantitatively by means of a set of specific **performance indicators**. From the above discussions, quantification of a system is primarily by its states of components and rates of flows. Accordingly, a performance indicator may be defined based on one or several states (termed a **state indicator**), one or several flows (termed a **flow indicator**), or a combination of state(s) and flow(s) (termed as a **state-flow indicator**). An example of state indicator for a vegetation ecosystem is the carbon or nitrogen stock in the soil (each being a state), or the ratio between these two states. A flow indicator can relate for example the rate of aquifer recharge and the aquifer extraction rate (both as a flow rate). A state flow indicator can relate the rate of water extraction (a flow rate) and the water storage in an aquifer at certain point in time (a state).

<heading level 2> Physical view

In parallel with the functional view and the performance view, the physical view classifies the rather abstract concepts of a system's structure and behavior according to their physical natures, which is closely related to the mathematical modelling of the system's behavior as the latter is typically based on physical principles. In this work, only a high-level classification of system components is presented via three major types of component which typically exist in a local system: ecosystem, technological and human being.

The **ecosystem** component is made up of natural environments such as a forest, a lake or a wetland and are classified into **biotic** and **abiotic** components. Within abiotic components, **land** includes mainly soil as source/sink of nutrients such as nitrogen and carbon; and **air** focuses on the material and energy flows exchanged with the other components, especially water, pollutant and solar radiation flows. The man-made **technological** components are artifacts resulting from human activities such as a power plant or a processing facility. Such components can be classified into building, equipment and machinery, and infrastructure which form the physical basis for industrial, agricultural, commercial, municipal and other civil operations. For example, energy production requires equipment (such as tanks, reactors, turbines), buildings for operation and management, and infrastructure (such as storage space and piping).

The **human** component is made up of social structures, ranging from individuals to organizations. **Individuals** and **families** or households are the units for understanding consumption. Individuals and families further form **communities,** where different patterns of consumption emerge**,** and **organizations** (such as companies, governments, NGOs), which devise and/or adopt policies, strategies or regulations pertaining to production and consumption. Human components are where most of the consumption takes place, setting the flows rates of products required to meet the needs of the local population.

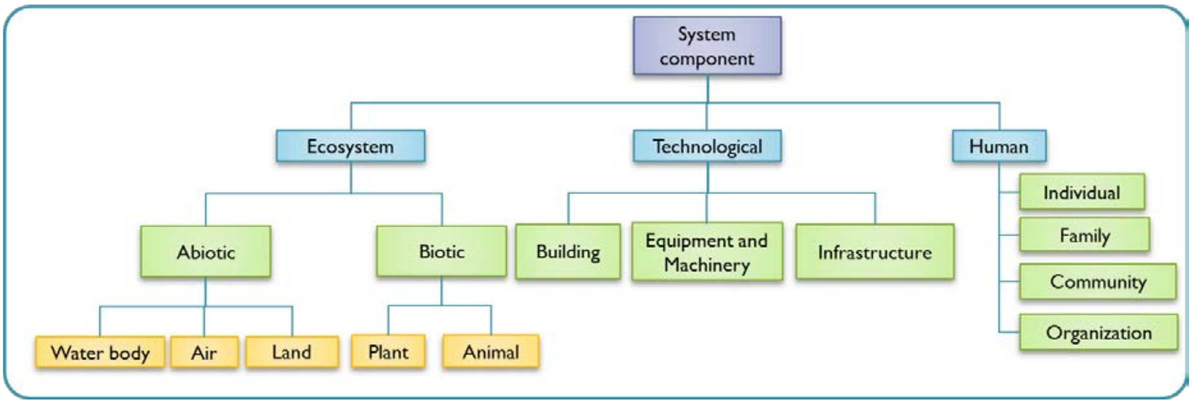


Figure 3. Components in the physical view.

<heading level 1> Mathematical characterization of local production systems

To quantitatively analyze or assess a system, mathematical characterization by means of modelling is required to predict or estimate the system’s behavior and performance.

<heading level 2> Behavioral modeling

Behavioral modeling generally includes state conservation equations as well as connectivity equations between components to model flow exchanges. A generic techno-ecological process model can be formulated following a system dynamics (SD) approach, similar to other parallel approaches for structured model construction, such as the one adopted by chemical engineering (Kröner et al. 1990; Morbach et al. 2007). The generic rate of change of a state (stock) variable *S* within a system component can be expressed as:

$$\frac{dS}{dt} = F_{in} - F_{out} - F_{cons} + F_{gen} \qquad (1)$$

where $\frac{dS}{dt}$ is the accumulation rate of the resource characterising the state (for example, nitrogen in soil)

F_{in} and F_{out} are input and output flows to and from the system, respectively

F_{cons} and F_{gen} are the resource consumption and generation rates of processes within a component’s boundary, respectively

Constitutive equations representing the rates of flows, consumption and generation can be introduced, depending on the physical nature of the processes involved. These equations for generation or consumption rates of a process can be expressed as a function of a process rate constant k_p, a state variable S, and/or a flow F.

$$F_p = f(k_p, S, F) \qquad (2)$$

In addition to balance and constitutive equations, some connectivity equations modeling the structural relationship between system components are required. A generic connectivity equation can be expressed as shown in equation 3.

$$F_{in}{}^{i,j} = F_{out}{}^{k,m} \tag{3}$$

where $F_{in}{}^{i,j}$ stands for the j^{th} inlet flow of component i, and $F_{out}{}^{k,m}$ the m^{th} outlet flow of component k.

These models may be simplified later according to specific assumptions and analysis of influence of the various process rates.

<heading level 2> Performance modelling

A performance indicator is modeled as a function of one or more states, a function of one or more flows, or a function of both:

$$I_s = f\left(S_1, S_2, \dots, S_{i,\dots,} S_n\right) \tag{4}$$

$$I_f = h\left(F_1, F_2, \dots, F_{j,\dots,} F_m\right) \tag{5}$$

$$I_{sf} = g\left(S_1, S_2, \dots, S_{i,\dots,} S_n, F_1, F_2, \dots, F_{j,\dots,} F_m\right) \tag{6}$$

where I_s, I_f, and I_{sf} are a state indicator, a flow indicator, and a state-flow indicator, respectively, and S_i and F_j represent a state and a flow, respectively.

Figure 4 synthesizes the overall system characterization framework. In a particular application the system characterization starts with defining the temporal and spatial scopes. Then, structural characterization follows to identify the components to be included in the analysis according to the objective of the study. With a specific set of performance indicators in mind, states and flows are subsequently identified, followed by the identification and characterization of the processes affecting the important states and flows. It is particularly important at this point to identify those processes and flows leading to key connections that can potentially enhance (or otherwise) the system in terms of resource efficiency, ecosystem health or other performance indicators. Examples of such connections include looping and matching between sources and demands through recycling, reuse and regeneration of resources. Next steps are mathematical modeling, collection of input data and setting parameters before proceeding to calculations and assessment.

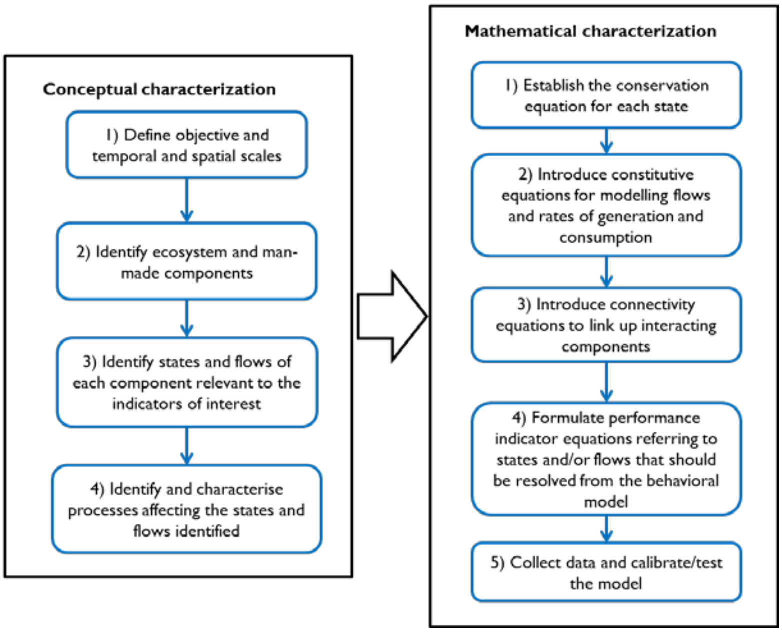


Figure 4. Overall framework for modelling local production systems with techno-ecological interactions

<heading level 1> Application of the modeling framework to a bioenergy production system

A case study within the context of the Whitehill and Bordon Eco-town in the UK (Whitehill and Bordon 2012) was undertaken, which addresses a system consisting of bioenergy production from heathland biomass (Woodcock and Stephens 2012) and sewage sludge as locally available resources for meeting local heat and electricity demands, as shown in figure 5.

<heading level 2> Conceptual characterization

Step 1. The objective was to assess biomass resource availability and the effect of the integration between energy production and the ecosystem. The spatial scope is that of the Whitehill and Bordon eco-town including its heathlands areas. Heathlands are an important ecosystem in the UK and Europe dominated by heather species (e.g. *Calluna vulgaris*), co-existing mainly with grass species (e.g. *Deschampsia flexuosa*). The temporal scope is a management timeline of 50 years. The final performance indicators of interest are a) the demand satisfaction rate as the percentage of energy that can be supplied to the eco-town whilst maintaining the heathland ecosystem, and b) the carbon storage in the ecosystem. Although these are reasonable indicator choices given the focus on the provision of energy, other important factors such as the structural changes of the eco-industrial network and ecosystem patterns that influence the functioning of the overall system should be considered in future work for a better evaluation of environmental sustainability.

Step 2. The main ecosystem component is the heathland. The technological components include energy production and sewage treatment and an aggregated component including residential, commercial and industrial buildings.

Step 3. The states and flows relevant to the indicators of interest are identified. To determine the amount of bioenergy production, the relevant flows are the biomass harvest rate and the nitrogen inputs (deposition from air and fertilization by nitrogen recycling). To ensure the heathland is maintained, the amount of standing biomass and nitrogen in soil, as key states, need to be tracked.

Step 4. The processes that affect the states and flows identified are recognized. Processes in components outside the boundary in figure 5 (air component and water body components), were out of the scope of this case study. Table 1 summarizes the mapped components, states, processes and flows relevant for the analysis. The relationships between processes, states and flows are described as follows.

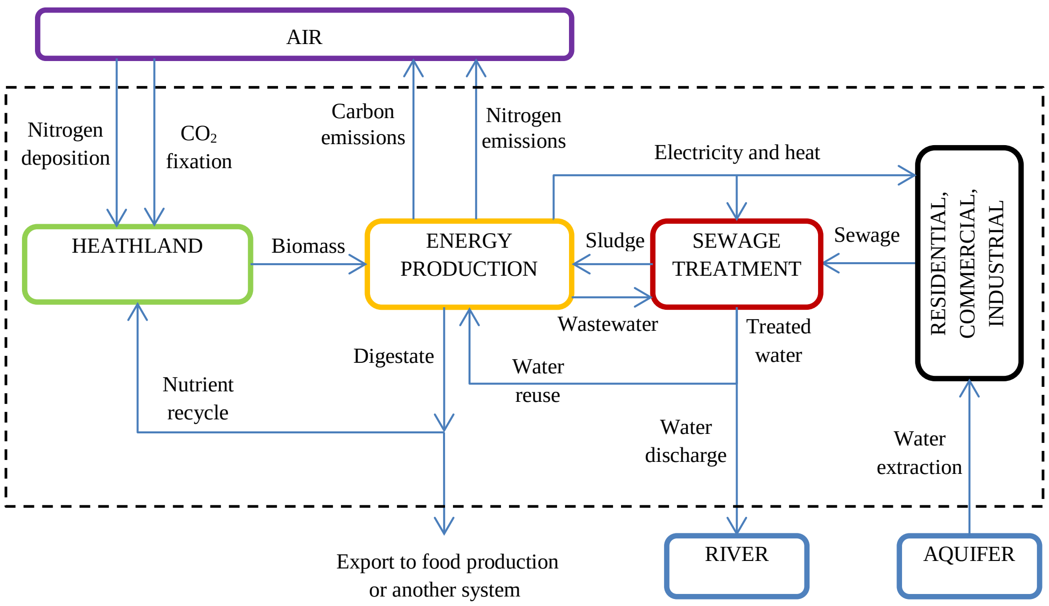


Figure 5. The local production system as analyzed in the case study**.**

In the heathland, heather (Calluna vulgaris) and grass species (Deschampsia flexuosa) compete for land and nutrients (Heil and Bobbink 1993; Bakema et al. 1994). Although other nutrients are needed for plant growth, this work focuses on nitrogen due to its distinct importance to maintain heathland ecosystems. Standing biomass of heather and grass and the nitrogen stock in the soil are the main states in the heathland component. Such states are affected by the processes of biomass growth, mortality and harvesting. Growth rate is affected by nitrogen availability from atmospheric nitrogen deposition, mineralization of litter in heathland soil, and nutrient recycling from the energy production component. At this point, a symbiotic relation can be created whereby the (necessary) removal of nitrogen from the ecosystem is carried out by biomass harvesting; such biomass exported from the ecosystem is then used as a renewable resource for energy production. The potential of harvesting *Calluna vulgaris* as a bioenergy crop has been studied recently by Worrall and Clay (2014), which facilitates the maintenance of the heathland by avoiding its transition into grassland due to overly increased nitrogen in the system (Power et al. 2001).

Table 1 System conceptual characterization of the bioenergy production system analyzed in the case study

Component (*type*)	**States** (*type*)	**Processes** (*type*)	**Input flows to component** (*type*)	**Output flows from component** (*type*)
Air (*ecosystem abiotic component*)	-	-	• **Nitrogen emissions** (*lost flow*) • **CO_2 emissions** (*recycled flow*)	• **Nitrogen deposition** (*regulating flow*) • **CO2 fixation** (*regulating flow*)
Heather and grass (*ecosystem biotic component*)	**Standing heather and grass biomass** (*supporting state*)	• **Biomass growth** (*production process*) • **Biomass mortality** (*consumption process*)	• **CO_2** (*regulating flow)* • **Nitrogen uptake** (*regulating flow*)	• **Nitrogen in litter** (*regulating flow*) • **Harvested biomass** (*provisioning flow*)
Soil (*ecosystem abiotic component*)	**Nitrogen stock** (*supporting state*)	**Mineralization** (*regulating process*)	• **Nitrogen in litter** (*regulating flow*) • **Nitrogen deposition** (*regulating flow*) • **Fertilizer** (*recycled flow*)	**Nitrogen uptake** (*regulating flow*)
Energy production (*technological component*)	-	• **Combined Heat and Power generation** (*production process*) • **Anaerobic digestion** (*production, regeneration process*)	• **Harvest woody biomass** (*provisioning flow*) • **Soft biomass to** (*provisioning flow*) • **Sewage sludge** (*recycled flow*)	• **Carbon and nitrogen emissions** (*lost flow*) • **Electricity** (*provisioning flow*) • **Heat** (*provisioning flow*) • **Fertilizer** (*provisioning flow*)
Sewage treatment (*technological component*)	-	**Sewage treatment** (*regeneration process*)	**Sewage water** (*degraded flow*)	**Sewage sludge** (*recycled flow*) **Treated water** (*regenerated flow*)
Residential, commercial and industrial (*technological component*)	-	**Consumption** (*consumption process*)	**Electricity** (*provisioning flow*) **Fuel for heat** (*provisioning flow*)	**Sewage water** (*degraded flow*)

The digestate from the anaerobic digestion (AD) process is assumed to be treated and used as fertilizer in the heathland to increase biomass productivity, within the ecosystem limits. Here is where another techno-ecological interaction can be established between bioenergy production and ecosystem. This either contributes to the maintenance of nutrient resources within the system or can be exported as a product. Treated water from the sewage treatment process can be reused for the AD of soft biomass and sewage sludge. At the same time, the wastewater from the dewatering of digestate can be treated in the sewage treatment process. Furthermore, the heat and power produced from the resulting biogas can help to offset the energy demand by the water management system. This not only creates an interesting symbiosis between technological components (Layton et al. 2015; Jacobsen 2006) but also indirectly benefits the ecosystem component by saving freshwater extracted from local aquifers. To analyze the effect on water requirements and supply, water state could be also modelled, although for the purpose of illustrating the modelling framework this work has focused only on nitrogen, the main limiting resource for the heathland ecosystem.

<heading level 2> Mathematical modeling

Mathematical characterization is exemplified using part of the model for the heathland ecosystem component. Heathland ecosystem models have been calibrated and tested using long-term field manipulation experiments (Power et al. 2004; Heil and Bobbink 1993; Bakema et al. 1994), and are combined here with models developed for the technological components. More detailed models and parameter values are presented elsewhere (Martinez-Hernandez et al. 2015).

Step 1. The behavioral modelling comprises establishing conservation equations for each of the relevant states (standing biomass and nitrogen in soil in this case). In the case of biomass state, there is no input flow but there is a generation rate due to biomass growth and a consumption rate due to mortality (litter production), and harvesting is the output flow. The rate of change of standing biomass (*B*) with time can be expressed as:

$$\frac{dB}{dt} = F_{growth} - F_{mort} - F_{harv} \qquad (7)$$

where *t* is time, F_{harv} is the harvest rate (an output flow), F_{mort} is the mortality rate (consumption) and F_{growth} is the biomass growth rate (generation). Nitrogen (N) availability is a triggering factor for the conversion of heathland into grassland or wooded land (Bakema et al. 1994; Power 2001). The tracking of accumulation of N in soil can also help to assess the nitrogen use efficiency by the system. N state in soil is determined by:

$$\frac{dN}{dt} = F_{dep}^{N} + {F_{in}}^{h,f} + \sum_{s} \left[\left(F_{mort,s} - F_{growth,s} \right) y_{N,s} \right] \qquad (8)$$

where ${F_{in}}^{h,f}$ is the inlet fertilizer to the heathland component, F_{dep}^{N} is the atmospheric nitrogen deposition; $F_{mort,s}$ is the mortality or litter production rate of the species *s*; $y_{N,s}$ is the nitrogen content in the biomass of species *s*.

Step 2. The constitutive equations for the input and output flows and generation and consumption rates involved. For example, the growth rate of species *s* ($F_{growth,s}$) is expressed in a generic form as:

$$F_{growth,s} = \frac{dB_{s}^{growth}}{dt} = k(N) B_{s} L(B_{s1}, B_{s2}, N) \qquad (9)$$

where $k(N)$ is the growth rate constant as a function of nitrogen availability (*N*); $L(B_{s1}, B_{s2}, N)$ is a competition function of the Lotka-Volterrra form in terms of heather (*s*1) and grass (*s*2) biomasses and nitrogen availability (Heil and Bobbink 1993; Martinez-Hernandez et al. 2015).

The harvesting rate is expressed in terms of the annual cut fraction f_{cut} and the standing biomass state:

$$F_{harv,s} = f_{cut} B_s \tag{10}$$

The rate of mortality of species *s* can be expressed as:

$$F_{mort,s} = k_{m,s} B_s \tag{11}$$

where $k_{m,s}$ is the mortality or litter production rate constant of species *s*, expressed in terms of standing biomass B_s.

The slowest processes are mainly those in the ecosystem, thus the energy production and sewage treatment processes can be considered to operate in steady state. Significant variations in these processes are caused by the variations in the supply of heathland or sewage biomass, which in turn changes with biomass yield and local human population, respectively. Thus, population dynamics were considered in order to capture such variability in the sewage flow and energy demands. The model for human population (HP) in the human-being component for the particular case of Whitehill and Bordon (curve fitted from data reported in Whitehill and Bordon Ecotown 2012) is:

$$HP = 1917 + \frac{6906}{1 + e^{(829.0776 - 0.4099 \times year)}} \tag{12}$$

Step 3. The connectivity equations are exemplified by the synergistic connections between the heathland and the bioenergy production component:

$${F_{in}}^{ep,b} = {F_{out}}^{h,b} \tag{13}$$

$${F_{in}}^{h,f} = {F_{out}}^{ep,f} \tag{14}$$

where ${F_{in}}^{ep,b}$ is the inlet biomass flow to the energy production component, ${F_{out}}^{h,b}$ is the outlet biomass flow from the heathland component, ${F_{out}}^{ep,f}$ is the outlet fertilizer flow from the energy production component that is recycled back to the heathland.

Step 4. In this step performance modelling is carried out by developing indicator equations in terms of the states or flows from the behavioral modelling. The indicators of interest are 1) for the case of the technological component, the energy demand satisfaction rate and 2) for the case of the ecosystem component, the level of carbon capture. These indicators depend on the biomass harvest flow rate, which in turn depends on the solution for the state variable of biomass in the heathland. The demand satisfaction rate also depends on the efficiency (or rates) of biomass conversion into heat and power by the technological processes. For example, the net electricity production can be estimated by:

$$F_{el} = A_h \left(\sum_s F_{harvest,s}\, y_{soft,s} k_{biogas} H_{biogas} \eta_{el}^{biogas} + \sum_s F_{harvest,s}\,(1 - y_{soft,s}) H_{wb} \eta_{el}^{wb} \right) \tag{15}$$

where A_h is the harvested heathland area, $y_{soft,s}$ is the soft fraction in the biomass from species s, k_{biogas} is the biogas yield from the input biomass flow, H_{biogas} is the heating value of the biogas produced from anaerobic digestion (AD), η_{el}^{biogas} is the electrical efficiency of the combined heat and power (CHP) plant using biogas, H_{wb} is the heating value of the woody biomass and η_{el}^{wb} is the electrical efficiency of the CHP plant using woody biomass. A similar equation can be obtained for heat production by replacing electrical efficiencies with thermal efficiencies. The demand satisfaction indicator can be calculated by:

$$\delta_e = \frac{F_e}{D_e} \times 100 \tag{16}$$

where δ_e is the demand satisfaction percentage, F_e is the energy supplied from the bioenergy production system and D_e is the demand of reference which can be the total demand of the locality, or the demand from a particular subsystem such as the industrial component.

Another indicator of the ecosystem is the level of carbon capture by the heathland ecosystem (in both soil and biomass). This state indicator can be calculated by solving the following equation:

$$\frac{dC_{(s+b)}}{dt} = \sum_s \left(\frac{F_{growth,s}}{f_{AG,s}} + M_s \right) y_C - C_{soil} k_{lossC} \tag{17}$$

where $C_{(s+b)}$ is the total carbon capture rate by the heathland ecosystem in the soil and biomass prior to harvesting, $f_{AG,s}$ is the fraction of biomass growth allocated to above-ground biomass of species s. Thus $\frac{F_{growth,s}}{f_{AG,s}}$ is the total net growth, including both above-ground and below-ground biomass (Martinez-Hernandez et al. 2015). M_s is the mortality rate of species s. y_C is the carbon fraction in the biomass. C_{soil} is the carbon stock in soil and k_{lossC} is the soil C loss rate constant. Due to data limitations, carbon emissions from the biomass harvesting process are not included.

<heading level 2> Quantitative analysis, results and discussion

The model equations were solved for annual biomass harvesting of 1600 ha of heathlands around the Whitehill and Bordon eco-town for a period of 50 yr. The local atmospheric nitrogen deposition is 16 kg ha^{-1} yr^{-1}. Model parameters and other inputs are reported elsewhere (Martinez-Hernandez et al. 2015).

The bioenergy production was analyzed with respect to the rate of biomass harvesting (in terms of cut fraction), the rate of nitrogen recycling, and the options for biomass conversion:

1) CHP production via direct combustion of the whole harvested biomass

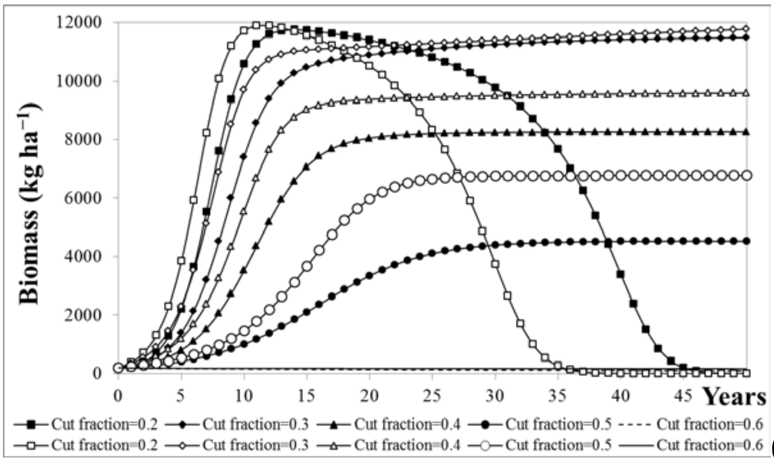
2) AD of soft biomass and using the biogas and woody biomass for CHP production

3) AD of sewage sludge to produce more biogas for CHP in addition to components in option 2.

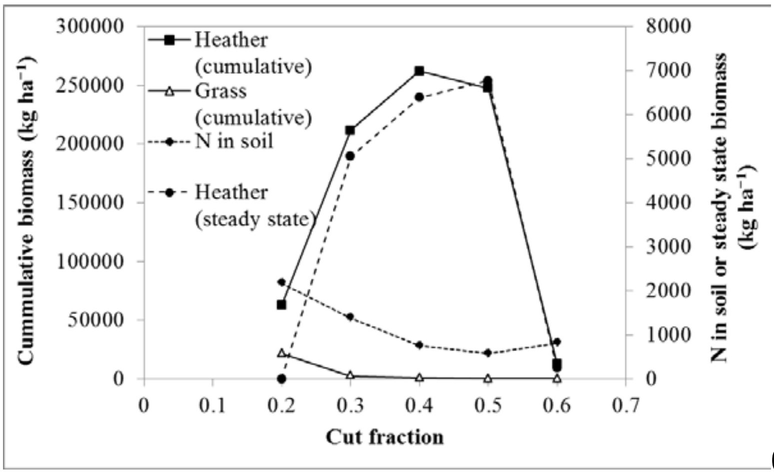
Note that only options 2 and 3 allow nitrogen recycling. The nitrogen that is recycled is the nitrogen originally present in the soft biomass that is recovered in the digestate resulting from AD.

The objective of this case study is to assess (i) how much biomass we can harvest while maintaining the ecosystem and (ii) the effect of symbiotic integration, as given by the biomass harvest and the nitrogen recycling. Figure 6a shows how both cut fraction and N recycle ratio affect the standing biomass in the heathland. Limited removal of heather biomass leads to a longer term decline in heather biomass. This is because insufficient removal of heather biomass allows nitrogen to accumulate in the soil, which in turn allows grass to gain an advantage and eventually replace heather (converting heathland into a grassland). However, it was found that a cut fraction of 0.6 or higher depletes the system faster than it can recover and both heather and grass biomass decline continuously. The nitrogen recycling via the digestate proves to be beneficial as it increases biomass yield. However, the influence of cut fraction with nitrogen recycling is similar to the system without nitrogen recycling. Figure 6b shows heather biomass that can be harvested and the nitrogen in soil at steady states for different cut fractions and 50% nitrogen recycle. Cumulative harvested biomass is also shown. If the steady-state performance is used as the criterion, a cut fraction of 0.5 optimizes the system as the yield is the highest and the nitrogen in soil is the lowest, thus achieving symbiosis between ecological and technological processes. If only the cumulative biomass production over the considered 50 years is considered, a cut fraction of 0.4 provides best results, however at the expense of higher nitrogen in soil, which may undermine the stability of the ecosystem.

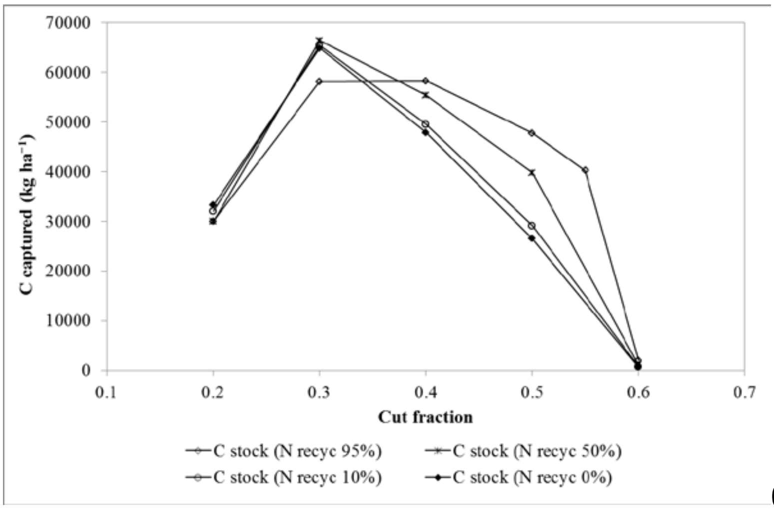
Another indicator of interest for this case study was the level of carbon capture in the ecosystem. Figure 6c shows the performance in terms of carbon captured in heathland (soil and biomass) after 50 years management under different regimes of cut fraction and N recycle. For low N recycles the carbon capture peaks at cut fraction of around 0.3, which is when heather starts becoming predominant. But at 95% N recycle the carbon capture peaks at higher cut fraction of 0.4. It can be observed that at cut fractions of 0.4 and beyond, the fertilization by N recycle from the energy production component increases the carbon captured in the heathland. However, it should be noted that the desirable high carbon captured comes at the expense of high accumulation of N in soil which can be detrimental for the ecosystem (Martinez-Hernandez et al. 2015).



(a)



(b)



(c)

Figure 6. a) Dynamic trends of standing heather biomass under varying cut fractions and no nitrogen recycle from soft biomass (filled markers) and with 50% recycle (open markers); b) harvested biomass at steady state, cumulative harvested biomass and nitrogen in soil after 50

years management and 50% nitrogen recycle, and c) cumulative carbon captured in the soil and biomass after 50 years management and 50% nitrogen recycle.

Following the above analyses, the indicator for the percentage of energy that can be supplied to the eco-town whilst maintaining the health of the heathland can be evaluated. Using a cut fraction of 0.5 and recycling 50% of the nitrogen in soft biomass, the system's biomass resources at steady state were estimated. The three bioenergy and water treatment design options, outlined earlier in this section, were compared in terms of percentage of demand supplied, energetic efficiency, nitrogen emissions and digestate exported as fertilizer, as shown in figure 7. Whilst Options 2 and 3 can supply higher amounts of the total electricity and industrial heat demands of the eco-town, Option 1 is better in terms of efficiency in energy conversion. However, the nitrogen emissions (which could increase nitrogen deposition in the local ecosystem) are higher in Option 1. Furthermore, Options 2 and 3 allow the recovery of nutrients thus producing significant amounts of fertilizer for agricultural production. This could also be integrated locally or exported to another local production system. Final decision requires an economic analysis, consideration of environmental policies as well as the criteria of the decision makers. Furthermore, consideration of the whole life cycle and all significant carbon flows and environmental impacts well deserves further research so as to ensure that decisions made to enhance interactions with ecological systems at the local scale, do not have compromising implications at another stage in the life cycle and possibly at larger scales. In fact, the cumulative resource consumption of each flow that enters a local production system has been considered in a separate work (Leung Pah Hang et al. 2014; Leung Pah Hang et al. 2015). Besides, methodological frameworks have been presented by Hanes and Bakshi (2015) and Bakshi et al. (2015), which address analyses across multiple scales. The framework shown in the present paper complements these broader studies by providing the necessary detail on local techno-ecological interactions which can then be analyzed in the bigger picture.

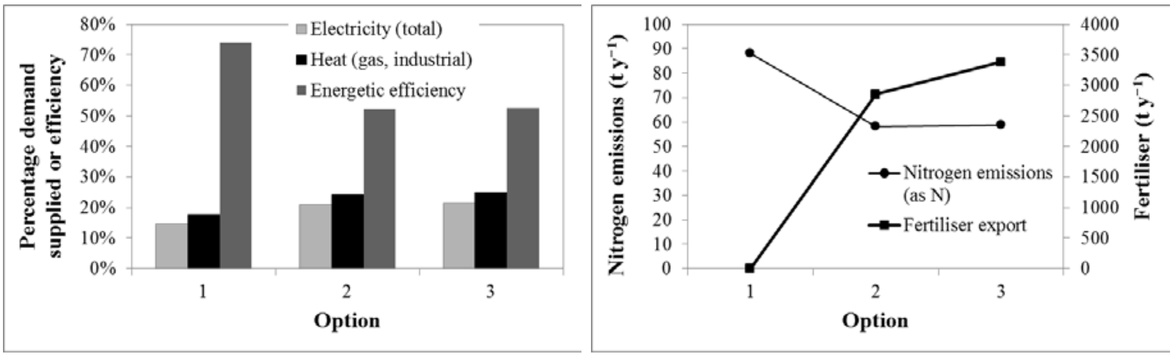


Figure 7. a) Percentage of demand that can be supplied by the three options for the local energy production system analyzed; and b) Nitrogen emissions and fertilizer exported by the various options.

The case study effectively shows how the framework encourages exploration of the interactions between the ecological and technological processes, asking: which interactions can potentially enable a symbiotic connection? Which supporting states need to be taken care of in order to maintain the provisioning of resources such as biomass? Which processes affect such states and the flow of the resource of interest? These are key questions that help to conceptualize and devise options for symbiotic local production systems with techno-ecological interactions. This kind of interaction was also the focus of the development of a flow matchmaker for eco-industrial parks and remote exchange of flows at regional or national levels (Brown et al. 1997).

<heading level 1> Conclusions

The system modeling framework proposed in this article, comprising a high-level conceptual model, a generic mathematical model, and generic procedures for constructing conceptual and mathematical models for localized production systems, was shown to be useful for devising options for a local energy production system which integrates both ecological and technological processes in a symbiotic way. The presented case study demonstrated how the framework can be applied to assess various design and operational options concerning the interactions between a heathland ecosystem, bioenergy production and wastewater treatment. By explicitly analyzing the two-way connections between the technical and ecosystem components, the framework also provided insight into the output of the energy production system and the corresponding level of the ecosystem states critical for the continuous provisioning of resources. The study of interconnected production, consumption and waste treatment components interacting within a local production system, with conscious integration with the relevant ecosystem components, could help to devise future systems that contribute to the sustainable development of local areas, whether small towns, villages, cities or regions. This means expanding the system boundary from that of production systems alone – a limitation that work in certain areas of industrial ecology such as the development of eco-industrial parks has the potential to overcome - to that of a broader techno-ecological system, and revealing complex interactions between different types of system components. It is envisaged that the framework presented here can be implemented in a decision support software system for scenario building and optimization towards sustainable local systems of production and consumption.

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<heading level 1> References

Bakema, A. H., R. Meijers, R. Aerts, F. Berendse and G. W. Heil. 1994. *HEATHSOL: A Heathland Competition Model*. Netherlands National Institute for Public Health and the Environment (RIVM).

Bakshi, B. R., G. Ziv, M. D. Lepech. 2015. Techno-Ecological Synergy: A Framework for Sustainable Engineering. *Environmental Science and Technology* 49: 1752−1760.

Brown, J., D. Gross, and L. Wiggs (1997). The MatchMaker! System: Creating Virtual Eco-Industrial Parks. In: Chertow M. (2002). Developing Industrial Ecosystems: Approaches, Cases, and Tools. Yale F&ES Bulletin 106.

Chertow M. and J. Ehrenfeld. 2012. Organizing self-organizing systems. Toward a theory of industrial symbiosis. *Journal of Industrial Ecology* 16(1): 13–27.

Curtis, F. 2003. Eco-localism and sustainability. *Ecological Economics* 46: 83−102.

Desrochers, P. 2001. Cities and Industrial Symbiosis: Some Historical Perspectives and Policy Implications. *Journal of Industrial Ecology* 5(4): 29–44.

Eckelman M. J., W. Ashton, Y. Arakaki, K. Hanaki, S. Nagashima and L.C. Malone-Lee. 2014. Island waste management systems. Statistics, challenges, and opportunities for applied industrial ecology. *Journal of Industrial Ecology* 18(2): 306–317.

Fröhling M., F. Schwaderer, H. Bartusch and F. Schultmann, 2013. A material flow-based approach to enhance resource efficiency in production and recycling networks. *Journal of Industrial Ecology* 17(1): 5–19.

Hanes, R. J., and B. R. Bakshi. 2015a. Process to planet: A multiscale modeling framework toward sustainable engineering. *AIChE Journal* 61(10): 3332–3352.

Hardy, C. and T. E. Graedel. 2002. Industrial ecosystems as food webs. *Journal of Industrial Ecology* 6(1): 29–38.

Heil, G.W. and R. Bobbink. 1993. CALLUNA a simulation model for evaluation of impacts of atmospheric nitrogen deposition on dry heathlands. *Ecological Modelling* 68(3–4): 161–182.

Hiete M., J. Ludwig and F. Schultmann. 2012. Intercompany energy integration. Adaptation of thermal pinch analysis and allocation of savings. *Journal of Industrial Ecology* 16(5): 689–698.

Jacobsen, N. B. 2006. Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects. Journal of industrial ecology, 10(1-2): 239-255.

Johansson, A., P. Kisch and M. Mirata. 2005. Distributed economies - A new engine for innovation. *Journal of Cleaner Production*, 13, 971-979.

Korhonen, J. 2004. Industrial ecology in the strategic sustainable development model: strategic applications of industrial ecology. *Journal of Cleaner Production* 12(8–10): 809–823.

Kröner, A., P. Holl, W. Marquardt and E. D. Gilles. 1990. DIVA−an open architecture for dynamic simulation. *Computers and chemical engineering* 14(11): 1289−1295.

Layton, A., B. Bras, and M. Weissburg. 2015. Industrial Ecosystems and Food Webs: An Expansion and Update of Existing Data for Eco-Industrial Parks and Understanding the Ecological Food Webs They Wish to Mimic. *Journal of Industrial Ecology*, Online Version of Record, DOI: 10.1111/jiec.12283.

Layton, A., J. Reap, B. Bras, and M. Weissburg. 2012. Correlation between thermodynamic efficiency and ecological cyclicity for thermodynamic power cycles. PLoS ONE 7: 51841.

Leung Pah Hang M.Y., E. Martinez-Hernandez,, Leach M., Yang, A. 2014. A multi-level framework for resource accounting, *17th European Roundtable on Sustainable Consumption and Production*, 14-16 October 2014, Portoroz, Slovenia.

Leung Pah Hang, M.Y., Martinez-Hernandez, E., Leach, M., Yang, A. 2015. Engineering Design of Localised Synergistic Production Systems, *Computer Aided Chemical Engineering* 37: 2363–2368.

Liang, S., L. Shi and T. Zhang. 2011. Achieving dewaterization in industrial parks. A case study of the Yixing economic development zone. *Journal of Industrial Ecology* 15(4): 597–613.

Martinez-Hernandez, E., M. Leach and A. Yang. 2015. Impact of bioenergy production on ecosystem dynamics and services – A case study on heathlands. *Environmental Science and Technology* 49(9): 5805–5812.

Mattila, T., S. Lehtoranta, L. Sokka, M. Melanen and A. Nissinen. 2012. Methodological aspects of applying life cycle assessment to industrial symbioses. *Journal of Industrial Ecology* 16(1): 51–60.

MEA (Millennium Ecosystem Assessment). 2005. *Ecosystems and human wellbeing: synthesis*. Island Press, Washington DC.

Morbach, J., A. Yang and W. Marquardt. 2007. OntoCAPE—A large-scale ontology for chemical process engineering. *Engineering Applications of Artificial Intelligence*, 20 (2): 147–161.

Power, S.A., C. G. Barker, E. A. Allchin, M. R. Ashmore and J.N.B. Bell. 2001. Habitat management: a tool to modify ecosystem impacts of nitrogen deposition? *Scientific World* 1: 714–721.

Power, S.A.; Ashmore, M.R.; Terry, A.C.; Caporn, S.J.M.; Pilkington, M.G.; Wilson, D.B.; Barker, C.G.; Carroll, J.A.; Cresswell, N.; Green, E.R.; Heil, G.W. Linking field experiments to long-term simulation of impacts of nitrogen deposition on heathlands and moorlands. *Water Air Soil Poll*. 2004, 4 259-267.

RAE (Royal Academy of Engineering). 2011. *Infrastructure, Engineering and Climate Change Adaptation –ensuring services in an uncertain future*. ISBN 1-903496-61-6

Rumbaugh, J., I. Jacobson and G. Booch. 2004. *Unified Modeling Language Reference Manual*. US: Pearson Higher Education.

Song, X. and B. Frostell. 2012. The DPSIR Framework and a Pressure-Oriented Water Quality Monitoring Approach to Ecological River Restoration. *Water* 4: 700-712.

Urban, R.A. and B. R. Bakshi. 2013, Techno-Ecological Synergy as a Path Toward Sustainability of a North American Residential System. *Environmental Science and Technology* 47(4): 1985–1993.

Urban, R.A., B.R. Bakshi, G.F. Grubb, A. Baral, W.J. Mitsch. 2010. Towards sustainability of engineered processes: Designing self-reliant networks of technological–ecological systems. *Computers and Chemical Engineering*, 34(9):1413–1420.

Whitehill and Bordon. 2012. *Eco-town Masterplan*. Hampshire, UK.

Woodcock, M. and P. Stephens. 2012. *Potential biomass supply from local heathlands for energy*. Forestry Commission, UK.

Worrall, F. and G. D. Clay. 2014. The potential use of heather, Calluna vulgaris, as a bioenergy crop. *Biomass and Bioenergy* 64: 140–151.

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