

An insight-based approach for the design of integrated local food-energy-water systems

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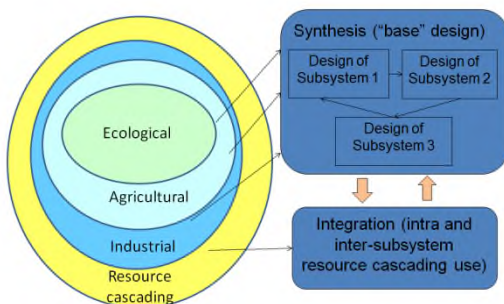
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KEYWORDS. Local production system, insight-based design, resource consumption, exergy, food-energy-water nexus

Graphical Abstract



ABSTRACT. Society currently relies heavily on centralized production and large scale distribution infrastructures to meet growing demands for goods and services, which causes socioeconomic and environmental issues, particularly unsustainable resource supply. Considering local production systems as a more sustainable alternative, this paper presents an insight-based approach to the integrated design of local systems providing food, energy and water to meet local demands. The approach offers a new hierarchical and iterative decision and

analysis procedure incorporating design principles and ability to examine design decisions, both in synthesis of individual yet interconnected subsystems and integrated design of resource reuse across the entire system. The approach was applied to a case study on design of food-energy-water system for a locale in the UK; resulting in a design which significantly reduced resource consumption compared to importing goods from centralized production. The design process produced insights into the impact of one decision on other parts of the problem, either within or across different subsystems. The result was also compared to the mathematical programming approach for whole system optimization from previous work. It was demonstrated that the new approach could produce a comparable design while offering more valuable insights for decision makers.

1. Introduction

In today's economy, centralized production and large scale distribution infrastructures provide the main mechanisms for meeting the demands for goods and services in fast developing economies. On the other hand, they are also causing problems such as uneven economic development, unsustainable resource consumption, and detrimental impacts on ecosystems¹. In the search for solutions, local production systems have been advocated as a possible sustainable alternative to the current centralized and globalized systems^{2, 3}. A local production system can be defined as a local network of geographically co-located heterogeneous processes (e.g. agricultural, industrial), integrated in a synergistic manner to achieve a high degree of resource efficiency, potentially leading to improved economic viability while preserving the ecosystem⁴.⁵. The geographical boundary of a local production system can be considered as that of an area under the direct governance of a local planning body. These systems offer the possibility to increase the use of renewable resources, avoid large transportation distances and allow customized system design based on local settings.

In this work, we are particularly interested in local systems for the provision of food, energy and water. Recognized by the term “food-energy-water nexus”, the interconnectedness between food, energy and water subsystems has recently been widely acknowledged at the regional, national and global scales^{6, 7, 8}. Though these three sectors are inextricably linked, these areas have too often been considered in isolation⁶. Thus, it is highly desirable to develop tools for analysis and design that consider their interdependencies⁹. To-date, a range of methods and tools has been developed for investigating the interconnected food, energy and water systems, including those for modeling and assessment^{10, 11, 12} and those for optimal design and planning^{13,14,15}. Most of the existing work however addresses larger (e.g. national and regional) scales. At the local scale, the design problem for a food-energy-water system can be defined as to determine the combination of processes which can meet a set of demands by a population in a locality within the availability of local resources so that total resource consumption is minimized while observing a set of technical, environmental and ecological constraints. As the local scale offers geographical proximity between different processes, optimization can not only consider general inter-dependencies between the food, energy and water systems, as is typically done by work on larger scales, but also explore symbiotic resource (e.g. heat, organic waste) reuse opportunities between specific facilities that can realistically be physically connected only at the local scale.

Our previous work⁵ has developed a mathematical programming (MP) based approach for designing local integrated production systems (LIPS) with a particular application to food, energy and water. A main limitation of this approach is that the solution process is entirely one of mathematically solving an optimization model: although a decision maker can be involved in constructing the model, what is presented to him or her is merely the final design, which makes it difficult to understand the impact of different factors, options, inter-subsystem interactions and trade-offs.

In this current work, an alternative, insight-based approach is developed. In the literature of process design and integration, the term “insight-based” typically refers to approaches based on pinch analysis which are in contrast with MP-based approaches^{16, 17}. Broadly, pinch analysis techniques encompass resource cascading and recovery based on thermodynamic principles, and have previously been applied to design systems involving heat¹⁸, water¹⁹ and hydrogen²⁰ exchange, to name a few examples. More recently, pinch analysis has been applied to the concept of a locally integrated energy sector^{21, 22} where heat and renewable energy sources are integrated and exchanged between diverse industrial processes.

In this work, the term “insight-based” is used with a broadened meaning: still in contrast with an approach purely based on mathematical programming which solves the design problem by using a monolithic optimization model, the insight-based approach aims to provide an incremental decision and analysis procedure incorporating design principles, which include pinch analysis techniques and design rules based on metrics measuring resource efficiencies to suggest and examine design alternatives. Such a decision procedure will produce insights to the decision makers such as the impact of choosing one option on the rest of the system and the comparative performance between different options. More importantly, with MP-based approaches, any insights are generated only at the end of the decision-modeling process ; in contrast, the incremental procedure (detailed in Section 2) would allow the decision makers to gain such insights at a series of intermediate steps, where they can also scrutinize, approve or reject the “optimal” options identified from the suggested design principles, possibly with considerations not explicitly covered by the design principles, and provide further information such as new design options and adapted parameter values that can be incorporated in the subsequent stages of the design process.

Although the insight-based approach is proposed as an alternative to the MP-based approach and highlights the use of design principles as opposed to optimization models and sophisticated algorithms, its step-by-step nature does not exclude, and in fact can readily incorporate, the use of MP to solve a sub-problem at a certain step, as demonstrated in the case study (Section 3.1.3). The flexibility of the approach also lies in the capability for supporting both new-design and re-design tasks. In fact, most of its practical applications will be for improving an existing local food-energy-water system. Using a generic concept of resource gain (Section 2.1), a new design option can be compared either with other new options or with the existing system. Although the latter case requires to consider both (i) the potential operational gain due to the new option and (ii) the cost for replacing the existing system with the new option (i.e. the retrofitting cost) (Section 2.3), the overall procedure applies equally well to both cases.

In the rest of the paper, we present the insight-based approach to the design of local integrated production systems (LIPS) for food, energy and water. This approach covers both (i) the generation of the basic design of individual subsystems taking into consideration their interactions and (ii) cross-subsystem integration to maximize the whole-system resource efficiency. Its application is demonstrated through a case study on an eco-town in the UK.

2. Methodology

The insight-based approach for LIPS design, as illustrated in Figure 1, consists of two main stages, namely synthesis (Sections 2.3 and 2.4) and integration (Section 2.5), guided by a Locally Integrated Production System Onion Model (LIPSOM) (Section 2.2).

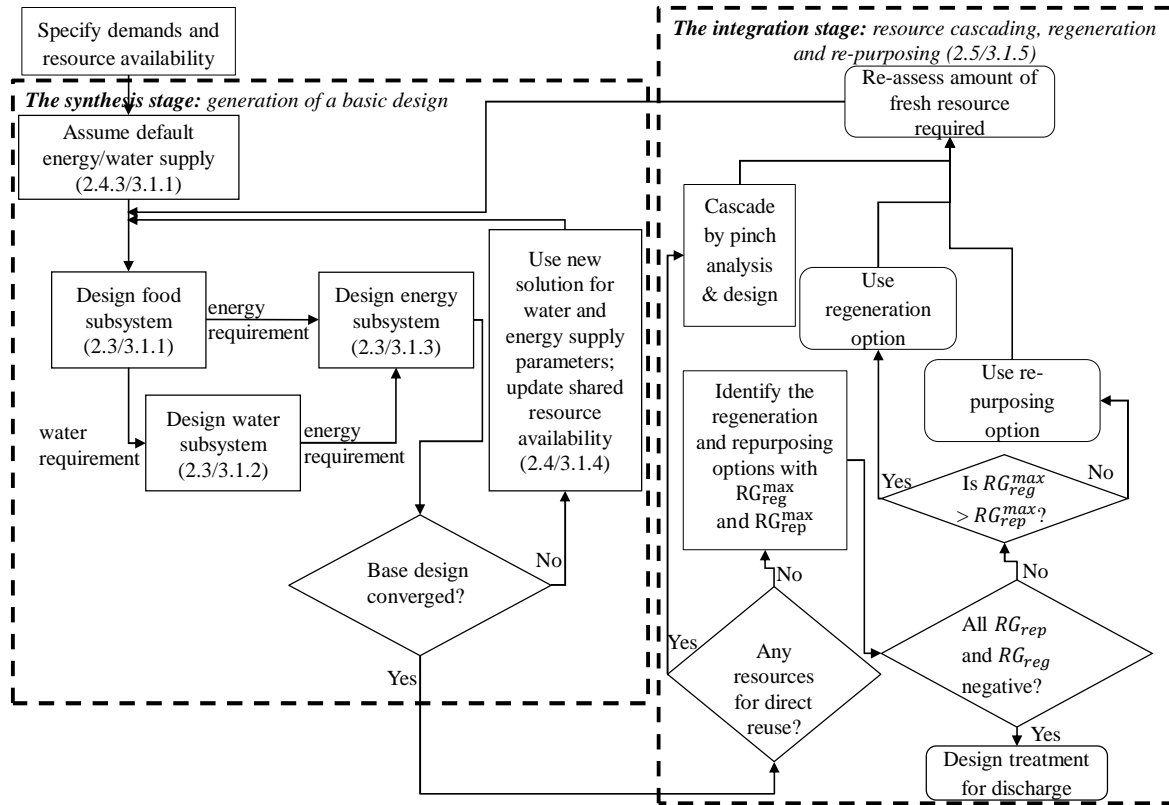


Figure 1. Design procedure for the insight-based approach. In the brackets are the corresponding section numbers in the methodology/case study parts of the paper.

The overall approach starts with the synthesis stage, to produce a “base” design of LIPS based on (i) principles for designing individual subsystems (Section 2.3) and (ii) a sequential synthesis procedure for converging the design of subsystems into that of the entire LIPS (Section 2.4). In the subsequent integration stage, options for cascading, regeneration and re-purposing of resource streams, which are not considered at the synthesis stage, are explored, the consequence of which may require revising the “base” design. Design decisions in both stages make use of the concept of “resource gain” (Section 2.1), to eventually achieve the goal of minimizing total resource consumption.

2.1 Design goal and resource gain

As in our earlier work⁵, the design goal is to minimize the total cumulative exergy consumption (CExC) of the LIPS in meeting the local demands and while satisfying resource and ecological constraints. CExC is defined as the sum of exergy of all resources consumed along the supply chain of a product/service²³. In the literature of resource accounting, CExC and several other exergy-based approaches have been proposed to offer a unified and thermodynamically rigorous quantification of resource requirements and environmental impacts^{24, 25, 26, 27}. In this work, CExC is used to capture the cumulative consumption of material and energy resources not only as inputs to the various stages leading to the supply of products and services, but also including the resource consumption for environmental remediation to tackle waste streams and emissions. However, it does not effectively cover a wide range of social and economic factors, for which additional tools are needed along with the approach proposed here.

As a key aspect of considering a LIPS is to assess its comparative performance against conventional options, e.g. satisfying local demands with external imports from centralized production, a resource gain (RG) indicator is introduced, which is defined as the net avoided CExC due to substitution of a reference (often conventional) option by a different, alternative option to be evaluated:

$$RG = CExC_{ref} - CExC_{alt} \quad (1)$$

$CExC_{ref}$ and $CExC_{alt}$ are the CExC by adopting the reference option and the alternative option, respectively. The nature of a design option being assessed depends on that of the corresponding decision to be made. The key types of decision are listed in Table 1, with an example of each type and the corresponding metric for making the decision. The metric is either RG as defined in Equation (1), or one that is derived from this RG.

Table 1: Type of decision tasks and metrics for decision making.

Decision task	Examples	Metrics
Producing locally or importing	Decision between producing bread locally or importing bread to satisfy local bread demands	RG as defined in Equation (1)
Selection of design technology/process options: new design	Decision between wind or solar for energy supply-	RG as defined in Equation (1)
Selection of design technology/process options: retrofitting design	Decision between introducing a wind power facility and continuing the use of grid electricity	Payback period of new capital resources, as defined in equation (3), Section 2.3
Selection of resource for a production process	Local or imported; fresh or re-generated	RG for regeneration options as defined in equation (4) , Section 2.5
Resource allocation between competing uses	Land for food and/or energy crops	Specific Resource Gain (SPR) as defined in Equation (2) below.

In particular, the last decision task in Table 1 requires the use of a slightly adapted concept, namely specific resource gain (SRG). A resource as provided by the local environment may serve multiple competing purposes and satisfy various demands. For example, crop residues as a resource, can either be used for animal feed or energy generation. Choosing one or another purpose may result in lower or greater resource consumption. In order to decide which purpose should be satisfied with priority, SRG is defined in Equation (2) as resource gain per resource quantity allocated to a particular purpose:

$$SRG = (CExC_{ref} - CExC_{alt})/F_r \quad (2)$$

where F_r is the resource quantity allocated. Between two alternative purposes, the one leading to a higher SRG should be given a higher priority in resource allocation due to the higher level of resource savings (measured by CExC) that can result from serving this purpose. As such, SRG for fulfilling a certain purpose in connection with a particular resource allows this purpose to be gauged with other competing ones, to support resource prioritization which may take place within (see Section 2.3) or between (see Section 2.4.2) subsystems.

2.2 LIPSOM: Locally Integrated Production System Onion Model

Design activities in the proposed insight-based approach are organized with the guidance of the LIPSOM, as shown in Figure 2.

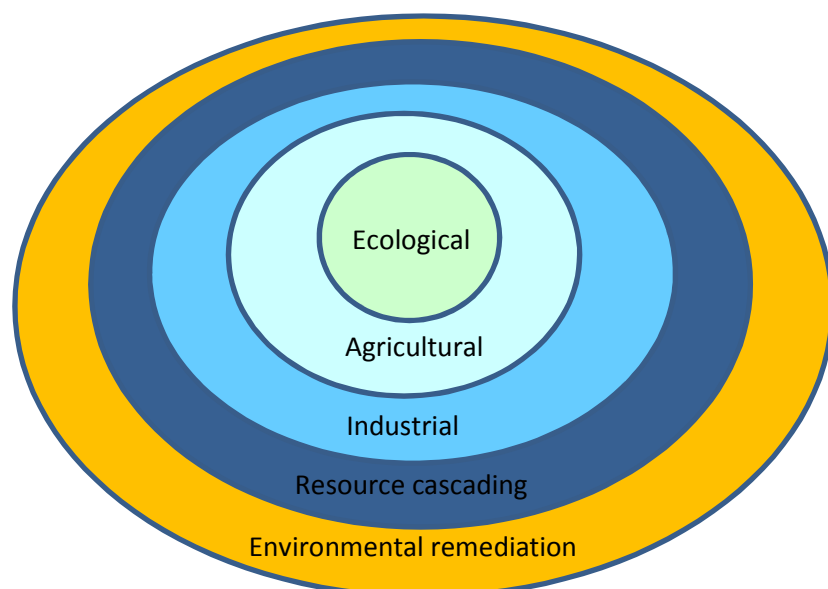


Figure 2: Locally Integrated Production System Onion Model (LIPSOM).

LIPSOM is based on the onion model developed by Douglas²⁸ as a conceptual design approach for process synthesis, in which a hierarchical procedure is followed starting from a reactor and gradually expanding the system boundaries as successive levels are added. The onion model highlights the sequence of design steps where each layer involves making design decisions that will affect those to be made in the successive layers of the model. As an adaptation to the original onion model, LIPSOM consists of five sequential layers and aims at capturing important interdependencies between them. The model starts with the ecological layer, to develop considerations on the local ecosystem consisting of components such as water bodies, atmosphere and land. The main purpose of design considerations at this layer is gathering ecological information such as the resources available and their constraints (e.g. biomass yield, land availability). This will offer important inputs to the subsequent design particularly with respect to resource selection and allocation, and identification of ecosystem components that

could be later interconnected to the production processes (e.g. wetland for wastewater treatment). Next, the agricultural layer addresses processes for producing food and non-food crops and livestock. In this layer, one can establish what agricultural processes can take place in the locale of concern, design options for each process, and the resource cost for each option. Locally available resources identified from the ecological and agricultural layers can be classified into: a) *basic resources* from existing ecosystems and the environment such as solar radiation, wind, forest biomass, that are unprocessed and unmanaged; and b) *managed resources* such as cultivated biomass, food crops and livestock. As suggested earlier²⁷, the cost of the basic resources is simply measured by their exergy content, while that of the managed resources is quantified by the cumulated exergy consumption across all the steps and activities for producing the resources.

The next layer is the industrial layer where industrial (including municipal) processing units are considered, such as those for food processing (e.g. bread production), energy conversion (e.g. solar panels), and water processing (for clean water supply or wastewater treatment). Process options, judged feasible based on the resource availability identified in the ecological and agricultural layers, will be identified and their resource consumption evaluated. Combined with the learning from the agricultural layer, this will enable the base design of subsystems, producing a final product to meet local demand (e.g. electricity or bread production); the principles for such design are outlined in Section 2.3.

In the resource cascading layer, any used or residual resources generated from the agricultural and industrial production processes (e.g. wastewater), which have not been fully utilized in the basic design, are considered for further utilization. As the process integration part of the insight-based approach, this layer takes into consideration all the process integration

opportunities within and across the subsystems, including options for regeneration and repurposing of resources.

The last layer comprises the design of environmental remediation units where either a technological or an ecological (e.g. wetland) option can be considered for the treatment of each of the resources identified from the cascading layer that cannot be further used for any purpose.

In connection with the two design stages introduced earlier with Figure 1, the ecological layer provides important information for the *synthesis* stage, where the base design of subsystems (food, energy, water) is carried out at the agriculture layer and the industrial layer. The resource cascading layer corresponds to the *integration* stage where further optimization can be applied. The final layer, environmental remediation, is considered in both stages when either a base design option or an integration option leads to discharges into the environment. In such a case, the cost for environmental remediation needs to be included in calculating the resource gain of the design option in question. The connection between LIPSOM and the overall design procedure is illustrated by the graphical abstract.

2.3 Principles for designing individual subsystems

A single subsystem of LIPS may involve components from ecological, agricultural and industrial layers. For example, a food subsystem could make use of local land and rain water to grow crops which are further processed into food products. Typically, the design of such a subsystem needs to incorporate considerations pertaining to all these layers, following several steps:

1. Identify the availability of local and external resources.
2. Identify technical options for agricultural or industrial processes required.
3. Determine resource implications for each resource or technical option.

4. Establish a reference system comprising conventional options, against which alternative, potentially more advantageous options can be compared.
5. Determine the design by choosing advantageous options based on resource gains.

Several details are given below for the final decision making step.

Firstly, at this step, RG is typically calculated for each alternative option, according to Equation (1), and an option with a positive RG, or one with the greatest positive RG when multiple alternatives exist, will be adopted. In some special cases where a retrofitting decision is to be made on whether a new and operationally more efficient technical component (e.g. an anaerobic digestion reactor for energy production) should be introduced, the operational RG, calculated as operational gain per unit time (e.g. per year) without considering resource consumption needed for building and installing the new component - referred to as capital resources - can be first calculated. Next, the period of time for the payback of capital resources (T) is determined as

$$T = \frac{C_{ExC_{cap}}}{RG} \quad (3)$$

with $C_{ExC_{cap}}$ denoting the CExC for capital resources associated with the new facility in question. This payback period, expressed in the same time unit as for calculating the operational gain, can then be compared with the decision maker's expectation or the service life span of the component, to determine its favorability.

Secondly, if multiple purposes (e.g. in agriculture, local production of bread or pork) within the subsystem compete for a limited resource (e.g. agricultural land), resource allocation will be based on the *SRG* (introduced in Section 2.1) of each of these purposes. In principle, the resource is to be used first to satisfy the purpose with the highest *SRG*, until the demand for

that purpose is met either fully or to the extent possible. If spare resource is still available, remaining purposes are satisfied in the descending order of *SRG*.

As the third point, the design needs to ensure that all the ecological limits identified in the ecological layer are met. In particular, the selection of a resource flow i needs to satisfy $\frac{c_i + x_i}{y_i} < 1$, where c_i is the current (existing) consumption, x_i is the (additional) quantity of the resource consumed for the design of the subsystem and y_i is the maximum quantity of the resource available locally according to either the natural replenishment rate or any authorized constraint (e.g. water abstraction limit set by water authorities). As another example, applying this condition to the ecological output of heathland biomass would mean that c_i is the current biomass consumption in the locale, x_i is the additional consumption for the design under consideration and y_i is the natural growth or replenishment rate of the biomass.

As a final remark, the above rules and principles could be sufficient for “manually” designing a subsystem where not too many options are to be assessed. However, when the number of options increases to a level which makes a manual design prohibitively complex, a mathematical programming problem could be formulated at the subsystem level to minimize total CExC of the subsystem while observing resource and ecological constraints as stated above.

2.4 Sequential synthesis of multiple subsystems

Beyond the design of individual subsystems, much of the complexity of synthesizing a whole LIPS lies in handling the connections and interactions between subsystems. This involves the determination of the sequence for designing the individual subsystems and the handling of inter-subsystem stream connections and resource allocation. In this section, principles for these tasks and an iterative design procedure for the complete process synthesis are presented.

2.4.1 Synthesis sequence

When designing a LIPS that involves multiple subsystems, one needs to decide the sequence in which subsystems should be considered to make the design process more efficient, by reducing the need for design iterations caused by subsystems' interconnections. As a general principle, the place of a subsystem in a design "queue" should be in accordance with the degree to which its design is affected by the design decisions of the other subsystems. The design of a subsystem typically depends on the following factors which are affected by the inter-subsystem connections:

(1) Availability of required resources

(2) Cost of required resources

(3) Product demand

If a subsystem requires a resource from another subsystem, then (1) and (2) could be affected by the latter subsystem via its capacity and efficiency respectively. If a resource is to be shared by other subsystems, (1) will be affected due to inter-subsystem competition. If the output of the current subsystem is input to another subsystem, (3) will be affected. For a food-energy-water system, each of the three subsystems involves interconnections affecting (1) and (2). In comparison, the food subsystem in most cases is simpler because its demand (i.e. (3)) is generally not affected by the other two subsystems. As such, it could be more independent, and therefore chosen to be designed first. However, the order between the two other subsystems is rather difficult to determine generally, and should be decided on a case-by-case basis. In the following, the design approach is explained assuming the water subsystem is more independent than the energy subsystem and hence should be designed first. It should be noted that the degree of independency of each subsystem may change, depending on the context. For example, if in a particular system the energy generation happens to heavily depend on the waste streams from

food production, theoretically the required output from the food subsystem may be affected by the energy subsystem, deviating from the more common case described above. In this and other situations where there is no subsystem which is significantly more independent than the others, one may randomly choose a subsystem as the starting point of the iterative design process. Note that the sequence of designing the subsystems affects the effort needed for reaching a convergence; it is not expected to change the converged design outcome.

2.4.2 Inter-subsystem resource allocation

In Section 2.3, a principle was presented for allocating a shared resource between multiple purposes in a single subsystem. If a resource is potentially shared by multiple subsystems, its availability to each subsystem needs to be updated when moving from the design of one subsystem to another. An example of this consideration is land allocation between growing food crops and energy crops. When the food subsystem is designed prior to the energy subsystem, all the agricultural land is considered as available for food production. When the energy subsystem is designed in a later step, if a technical component consuming energy crops (e.g. biomass Combined Heat and Power, CHP) is identified as a preferred option, and there is no sufficient land available for supplying energy crops due to the occupation by the food subsystem, its SRG needs to be compared with those of the options chosen in the food subsystem design. If the former turns out to be higher, land will be re-allocated from the food subsystem to the energy subsystem; and the former will be re-designed (in the next iteration, see Section 2.4.3) based on the reduced land availability.

2.4.3 A sequential synthesis procedure

Implementing a determined design sequence and handling inter-subsystem connections, a sequential iterative procedure for synthesizing a complete LIPS is proposed.

At the start of the procedure, synthesis will assume conventional utilities, without considering alternative sources that the local system can potentially offer. For example, the food subsystem uses grid electricity (as opposed to power from local renewables) and standard ground water (as opposed to rain water), as the cost information of these alternatives is yet to be produced later when the energy and water subsystems are designed. Following the design sequence determined in Section 2.4.1, the food subsystem is first synthesized, using the principles stated in Section 2.3, in isolation from the other subsystems. Then, the water subsystem is synthesized, but considering the water demands of the food subsystem just designed in addition to the other local water sinks (e.g. residential users). Alternative water streams that can be used by the food subsystem and the other local water uses and their associated CExC will be determined, and preferable options chosen. Lastly, the energy subsystem is synthesized taking into account the energy sources and sinks arising from the initial design of the food and water subsystems and other local energy demands, with examination of energy streams that can be generated locally or obtained from centralized supply and selections made.

Following the initial pass of design, the first iteration is carried out. The water and energy supply parameters from the initial pass are used and the same design sequence repeated. This particularly includes replacing any assumptions of using conventional utilities as adopted at the start of the design process with the energy and water supplies concluded from the initial pass of design. The iterative process stops when the quantity of resource streams (e.g. rainwater, solar power) exchanged between the three subsystems and their corresponding specific CExC become stable, and no further adjustment is needed for inter-subsystem land allocation.

2.5 The integration stage: resource cascading, recycling and regeneration

Following the synthesis stage, resource cascading can be carried out upon the synthesized base system. Cascading has often been applied in the context of resource scarcity as a resource conservation technique²⁹. In this work, it refers to the multiple re-use of a resource stream, resulting in quality degradation in each instance of use, in absence of quality up-lifting between uses. Two cases of cascading use of a resource can be identified:

(1) Same-purpose cascading use where the successive uses are based on the same quality of the resource (e.g. COD level) for that purpose, e.g. reusing water to satisfy water demands at different COD levels.

(2) Re-purposing where the next use of the resource is based on a quality different from that of its previous use. For example, repurposing might involve processing wastewater for nutrient recovery rather than for water supply.

A high quality resource is usually either expensive to produce or scarce. Therefore, the design of a series of cascading use of a certain resource generally aims to minimize resource costs by matching the quality “grades” of the resource with the levels of demand for quality. In fact, this is the common principle shared by the existing pinch analysis and design approaches¹⁸. These approaches are adopted for designing the cascading use of resources in LIPS.

At the end of a series of cascade steps, reprocessing could be undertaken to allow resources that would otherwise be wasted to be used again through the same process or through different type of processes. Re-processing may materialize in (i) upgrading or regeneration to improve the quality of a used resource to enable *recycling*, i.e. reuse of the resource in the same application, or (ii) any treatment needed to *repurpose* the resource. Options for recycling or repurposing are ranked according to their RG, evaluated by adapting equation (1):

$$RG = CExC_{avoided} + CExC_{treatment} - CExC_{rep} \quad (4)$$

where,

$CExC_{avoided}$ is the CExC of fresh or other resources avoided by recycling or repurposing;

$CExC_{treatment}$ is the CExC for treating waste that would arise from the used resource if it was not reused through recycling or repurposing;

$CExC_{rep}$ is the CExC needed by the reprocessing to prepare for recycling or repurposing.

For each used resource considered, the recycling or repurposing option with the highest RG is adopted.

At the end of the recycling/re-purposing analysis, any excess unused resources that are not worth being further utilized will have to be treated before being discharged into the environment. If different environmental remediation options exist for treating the unused streams, determine the CExC for each option and choose the one with the lowest $CExC_{env}$, $CExC_{env}^{min}$.

3. Results and discussion

This section presents a case study to demonstrate the application of the insight-based approach for designing a local integrated food-energy-water system, through the following aspects:

- Using RG based design principles to generate the base design of the water and food subsystems, and a linear programming assisted design of the energy subsystem.
- Using the sequential design procedure to produce a complete whole-system base design.
- Cascading use of wastewater and waste heat within and across subsystems.

- Assessing regeneration options for wastewater.

To simplify the case study, regeneration for waste heat source and re-purposing options for both wastewater and waste heat were not included. As no retrofitting decision was considered, the design principles based on the payback of capital resources were not demonstrated. Section 3.1 presents the main results from the various stages of the case study; all the detailed results, calculations and assumptions can be found in Supporting Information. In Section 3.2, comparisons are made between the resource consumption of the LIPS designed by the insight-based approach and that of a system relying on external, centralized supply and between the results of the insight-based approach presented in this work and those of the mathematical programming approach from our earlier work, to offer an overall assessment.

3.1 Application of the insight-based approach

The selected case study locale is the town of Whitehill and Bordon in southeast England, being regenerated into a sustainable green town; its ecological and climatic settings and demand data are obtained from the local development agency³⁰ and from central government^{31, 32}. Seasonal variations in both resource availability and demands are considered, by designing the subsystems separately for the four seasons, and considering cross-season storage for crops and rainwater. Throughout the case study, a number of quantitative results will be presented, which have been obtained based on a specific set of parameter values mostly adopted from literature. In reality, there are inevitably issues arising from data quality and uncertainties, which may impact on the reliability of individual results and consequent decision recommendations. There are established approaches to deal with these issues, such as sensitivity analysis and optimization with uncertainties, and these have in fact been applied along with the work on the optimal design of local food-energy-water systems³³, which however are not included here to allow this paper to focus on the main design approach.

3.1.1 Initial design of the food subsystem

The food products considered are bread, potatoes, pork and beef and have been chosen based on local food preferences in the eco-town. These food choices also give a good representation of a human being's dietary requirements in carbohydrate, protein and fats. With a total availability of 17 ha, agricultural land is a limited resource and as such the specific resource gain *SRG* of each food type, with the imported food as the reference option, was determined using Equation (2) (see Section 2.1 for the rationale behind the use of *SRG*). The food products with *SRG* values in decreasing order were bread, potatoes, beef and pork, at 3.17×10^4 MJ/ha, 9.29×10^3 MJ/ha, 6.02×10^3 MJ/ha, 1.02×10^3 MJ/ha respectively, resulting from the difference in the *CExC* value between the imported and the locally produced products, as well as the local yield, of each food type. Using the design principle for resource allocation, growing wheat for bread was given priority to receive land, and it turned out that all the land was to be allocated for this purpose and 60% of the bread demand could be satisfied by local wheat; while all other food demands needed to be imported due to limited agricultural land availability, despite their positive *RG*.

3.1.2 Initial design of the water subsystem

The initial design of the water subsystem needed to satisfy the water demand by bread manufacture from the food subsystem and the residential sector, with groundwater and rainwater as the sources available. The potential uses of rainwater at this stage were limited to wheat cultivation and non-potable domestic water uses. Using Equation (1) and taking groundwater as the reference resource, the *RG* for rainwater was determined to be -0.048 MJ/kg. The negative *RG* was due to the relatively high capital resources to implement a local rainwater harvesting system leading to groundwater being overall a more resource efficient

alternative for water supply. Groundwater has an abstraction limit in the eco-town; however this is sufficiently high²⁵ and therefore groundwater use was not limited by its availability.

3.1.3 Initial design of the energy subsystem

Alternative electricity generation sources from wood chip biomass CHP, organic waste CHP, natural gas CHP, solar and wind and heat generation from wood chip biomass boiler, wood chip biomass CHP, organic waste CHP and natural gas CHP were considered alongside grid electricity and heat from natural gas boilers as conventional energy sources. Agricultural residues produced from the initial design of the food subsystem are available in summer for energy production, which is assumed to be able to merge with organic waste from municipal operations to feed into a CHP facility. As using the RG based principles to design this subsystem manually would be too complex given the number of options to be considered, linear programming (LP) was adopted to generate a fast optimum design. The objective function of the LP problem was to minimize the net total CExC of this subsystem while meeting local heat and electricity demands, allowing the generation of surplus electricity if a CHP facility was selected.

When the difference between the CExC of locally generated surplus electricity and the CExC of grid electricity was taken as resource credit in the objective function, the optimal design of the energy subsystem was to produce most of its electricity output from wood chip biomass CHP (49.6%), followed by wind power (19.9%), solar (17%) and organic waste CHP (13.5%). Reflecting the resource credit assigned to the exported electricity, virtually all the power generated by CHP was surplus. The total heat demand for the eco-town was met fully by the wood chip biomass CHP (87%) and organic waste CHP (13%). This electricity mix corresponds to an average specific CExC of 1.90 MJ/MJ electricity; a significant 68% decrease from grid electricity. The average specific CExC of supplying heat was determined to be about

1.80MJ/MJ heat; which corresponds to a 10% decrease from that of supplying heat from conventional natural gas boilers. Furthermore, taking agricultural residues as feed for energy production resulted in a reduction of the total CExC required by 4% compared to not considering the residues.

If the resource credit of producing surplus power was not included in the objective function of the LP energy model, the energy supply for satisfying heat demand includes 13% organic waste CHP, 9.5% biomass CHP and 77.6% from wood chip biomass boiler while the electricity mix would comprise 50% wind, 14% wood chip biomass CHP and 36% organic waste CHP with no surplus electricity generated. The average CExC was determined to be 540,150 GJ/y compared to the average CExC of -41,361 GJ/y in the initial energy production subsystem; indicating that the inclusion of a credit for avoiding the CExC associated with grid electricity through local electricity export decreases resource consumption significantly; far offsetting the amount of resources spent to produce energy locally. The use of agricultural residues did not have any appreciable impact on the total CExC of such an energy system.

3.1.4 Iterative design

Following the initial pass of the sequential synthesis procedure, further design iterations were carried out. Table 2 shows the outcome of the 1st iteration, along with the insights gained from the change in the design outcome resulting from this iteration. The 2nd iteration was subsequently conducted, which did not alter the selection of design options, but the 15% decrease in energy consumption for groundwater use from the 1st iteration led to the change in the RG ranking of the food products, with beef now being more efficient to produce than potatoes, which suggests that beef production cost is rather sensitive to water supply. Also, although there were changes in the energy demand from the food and water subsystems, these changes were not significant enough to modify the optimal energy mix supplied by the energy

subsystem, suggesting the overall design was becoming stable. In fact, the convergence criterion was met following the 3rd iteration, marking the completion of the synthesis stage. The final base design is illustrated in Figure 3.

Table 2: Outcome of the 1st iteration.

Sub-system	Design outcome	Insights from initial to 1 st iterative design
Food	<p>Initial design:</p> <p>The food products with SRG values in decreasing order were bread, potatoes, beef and pork, at 3.17×10^4 MJ/ha, 9.29×10^3 MJ/ha, 6.02×10^3 MJ/ha, 1.02×10^3 MJ/ha respectively.</p> <p>1st iterative design:</p> <ul style="list-style-type: none"> - Bread still has the highest RG at 4.63×10^4 MJ/ha followed by pork at 1.16×10^4 MJ/ha, potatoes at 9.29×10^3 MJ/ha and beef at 3.63×10^3 MJ/ha. - 10% and 68% decrease in specific CExC for heat and electricity respectively. 	<ul style="list-style-type: none"> -With similar water but cheaper energy supply to its initial design, pork becomes the second cheapest food type to produce locally, indicating that pork is very sensitive to resource cost for energy supply. -Between beef and pork, the local production of the latter would still consume more energy than the former despite the change in energy cost per unit (kg), as the quantity of pork produced locally based on land available is higher than beef, with a land to pork ratio of 1.2 ha/ton compared to 4.7 ha/ton for beef²⁸.
Water	<p>Initial design:</p> <ul style="list-style-type: none"> - Specific CExC groundwater was 0.06 MJ/kg while RG for rainwater was -0.048 MJ/kg. <p>1st iterative design:</p> <ul style="list-style-type: none"> - Specific CExC groundwater was 0.051MJ/kg (a 15% decrease) while RG for rainwater was -0.06 MJ/kg. - New water demand and wastewater generation from energy production was met. 	<ul style="list-style-type: none"> - More resource-efficient using groundwater to satisfy all water demands in the eco-town rather than using rainwater due to its negative RG and also the relatively high abstraction limit for groundwater.
Energy	<p>Initial design:</p> <ul style="list-style-type: none"> - Electricity demand supplied by 52% wind, 45% solar and 3% wood chip biomass CHP. - Average specific CExC of 1.89 MJ/MJ electricity - Heat demand supplied by 87% wood chip biomass CHP and 13% organic waste CHP with an average specific CExC of 1.80 MJ/MJ heat <p>1st iterative design:</p> <ul style="list-style-type: none"> - Electricity demand supplied by 50.1% wind, 43.3% solar and 6.5% wood chip biomass CHP. 	<ul style="list-style-type: none"> - Contribution of wood chip biomass CHP, which has a relatively high specific CExC, in the electricity mix increased by 3.5% compared to the design from the initial pass due to the need to satisfy higher energy demands.

	- Average specific CExC of 2.02 MJ/MJ electricity; 6.5% higher than in initial design. -Same heat source mix as in initial design.	
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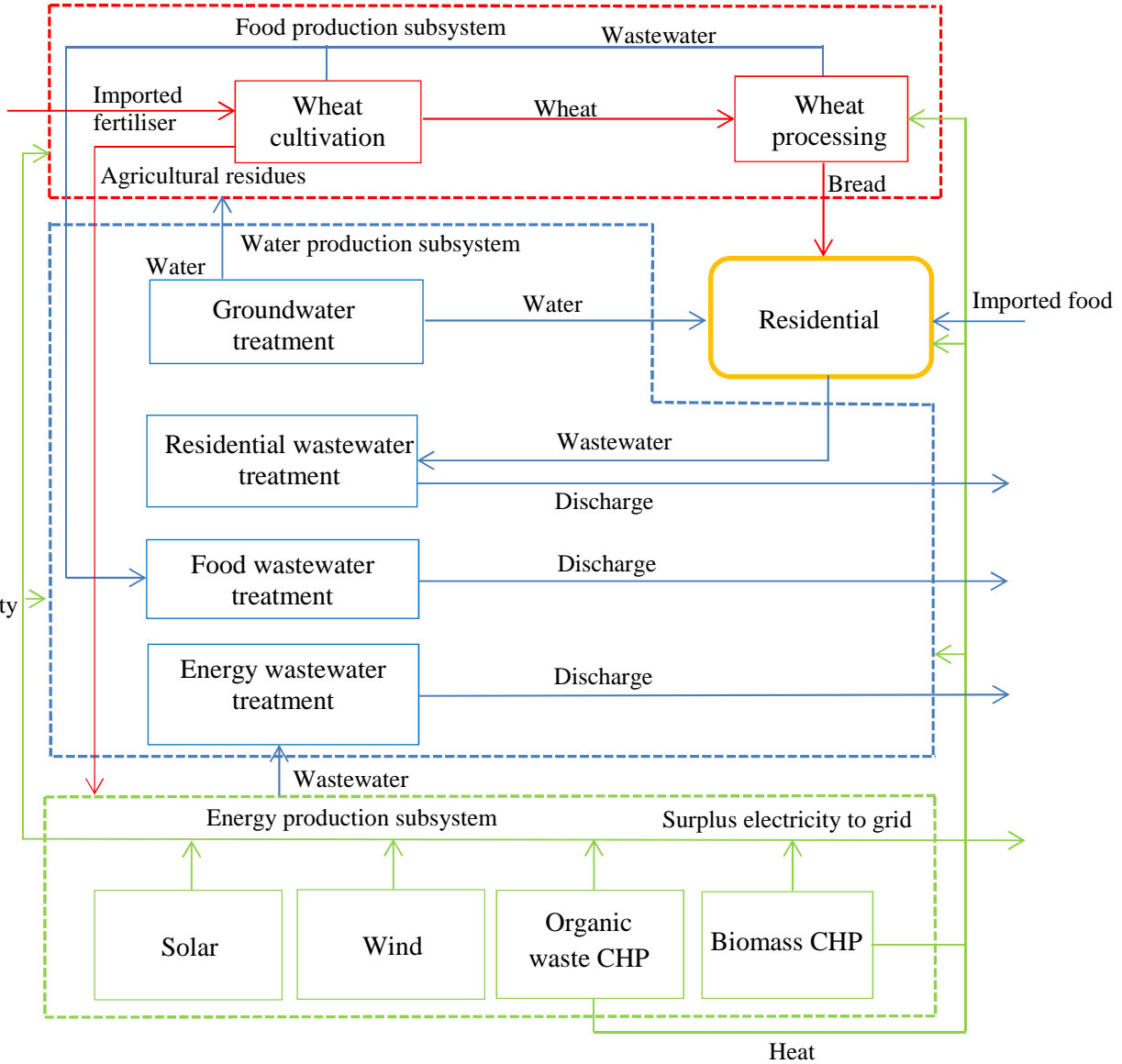


Figure 1: Base design of the local production system.

3.1.5 Integration: water reuse and regeneration

After the base design was generated, the system was optimized by considering integration options for resource reuse. As all the water sources considered had a COD level much higher than the COD requirements of any water sinks, from a quality perspective the cascade use of

the water sources through the application of pinch analysis would result in no possible recovery. As direct re-use was infeasible, options of regeneration (to enable reuse) were evaluated. The *RG* for regenerating different water sources of residential wastewater, wastewater from food production, wastewater from energy production up to the desired quality of the water sinks were assessed using Equation (3). Taking into account resource cost for environmental discharge of un-regenerated wastewater and the cost of fresh water avoidable by using regenerated water, the net specific CExC for regeneration was determined to be positive, hence supporting the regeneration option. The use of regenerated wastewater was limited to wheat cultivation, non-potable residential purposes and energy production, but not for food processing, in line with health and safety regulations²⁹. It was determined that about 61% of the eco-town's water demands could be satisfied by regenerated water sources, hence significantly reducing the consumption of groundwater. The average specific CExC of water supply was reduced by 60% from its original value in base design. The reduction in total CExC of the water subsystem did not impact the design decisions of the energy subsystem as water was not a significant component (less than 1%) of the specific CExC of the energy options. Any remaining unused streams were to be treated before environmental discharge.

3.1.6 Integration: energy reuse

Pinch analysis³⁰ was applied to optimize the use of heat available in each season. Low temperature (LT) waste heat available from organic waste CHP and wood chip biomass CHP was candidate for reuse to meet heat demands from industrial bread production, wheat storage, wastewater treatment plant and residential. It was determined that adopting 3 heat exchangers placed above the pinch would allow for maximum heat recovery of 2.79×10^7 MJ/y. The reuse of LT waste heat contributes to satisfying about 10% of the total heat demand. The proportion of high and medium temperature heat produced from wood chip and organic waste CHPs in

the heat energy supply mix decrease from 87% and 13% to 78.4% and 11.7% respectively. With this new heat energy supply mix, the average specific CExC of heat was reduced by 10% from its value from the base design. However, the new specific CExC for heat coupled with cheaper water supply did not alter the order of the *SPG* for the different food options, though *SPG* for pork followed very closely that of bread. Similarly, the design of the water subsystem was not changed.

Together, water and energy reuse design showed that the decisions in the integration stage did not lead to a qualitatively different design from the synthesis stage in this particular case. However, the base design was made more efficient, through the reduction in energy production required from the CHPs and the consumption of groundwater.

3.2 Comparative analysis and final assessment

To show the extent to which a LIPS, designed following the insight-based approach, can achieve resource savings, the results presented in Section 3.1 are compared with the resource consumption for meeting the same local demands by another scenario termed “centralized supply”, which imports food and utilities (grid electricity and natural gas). Figure 4 illustrates the external resource consumption of each subsystem for each scenario, which clearly demonstrates the resource advantages of the LIPS: when including the credit for exported surplus electricity, the LIPS consumes less than 10% of resource (measured in CExC) needed by the centralized supply scenario; a 39% saving is still achieved even without the aforementioned credit.

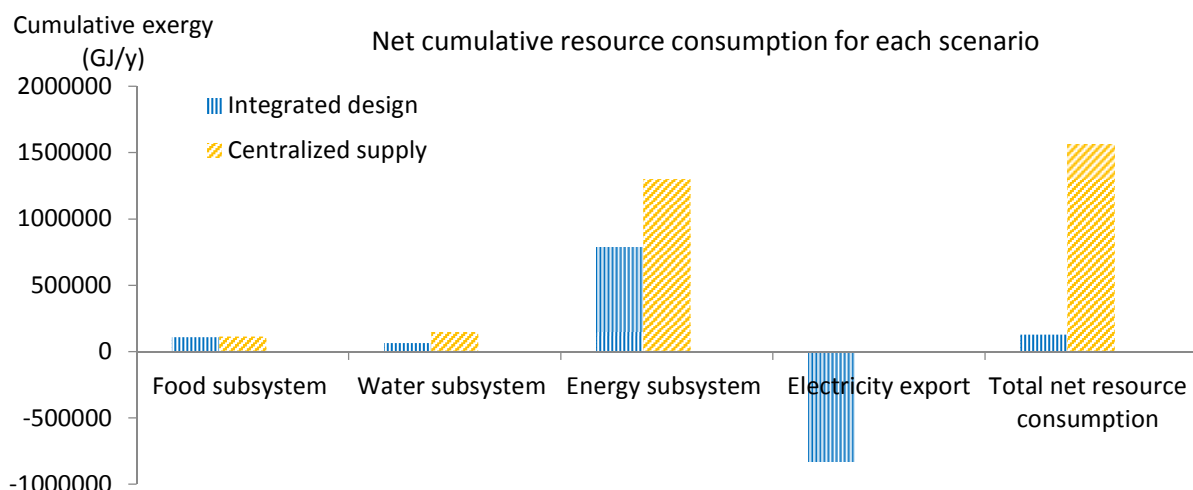


Figure 2: Comparison between the LIPS and the system with centralized supply.

The result of the insight-based design approach was also compared to that of the mathematical programming (MP) approach developed earlier⁵, which was adapted to include all assumptions and options for food, water and energy subsystems considered in this case study. The overall resource consumption of the two designs appeared to be similar, with the result of the MP approach being slightly better. A closer inspection of the design decisions by the MP approach (see SI) revealed that both approaches suggested qualitatively identical designs in terms of the food product and technical options selected for local production. Quantitatively, both designs suggested the same decision for the food subsystem, i.e. using all the land to meet 60% of bread demand. There were minor differences in the percentage of groundwater replacement by regenerated wastewater and in the energy mix proportions, and there was a noticeable (6%) increase in waste heat recovery identified by the MP approach. These quantitative gains by the MP approach are not surprising, given its adoption of rigorous and simultaneous mathematical optimization.

Overall, it can thus be inferred that the insight-based approach offers sensible and comparable design solutions. Compared to the purely MP-based approach, the extensive use of design rules (including those of pinch analysis and those based on decision metrics) and the incremental

nature of the insight-based approach make it more informative for the decision analyst to use, by allowing them to keep control of the decision process and to gain a proper understanding of the implications of various design options and their interactions, particularly those across different subsystems. Therefore, it offers an effective approach for practitioners to discover the superior designs of an integrated local production system for supplying food, energy and water to achieve significant resource savings than relying on centralized supply, through rational utilization of local renewables and resource sharing and exchange between different local production processes. Whichever approach is followed, significant savings have been demonstrated for a well-designed integrated local production system. However there will often be practical challenges in terms of data availability, an issue to be resolved by the combination of literature data sources (particularly for cumulative exergy consumption) and locale-specific data gathering.

ASSOCIATED CONTENT

Supporting Information: Data and parameters used in the models and ancillary information.

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ACKNOWLEDGMENT

Financial support from the Leverhulme Trust through the Project Grant RPG-2012-663 is greatly acknowledged. We would like to also thank three anonymous reviewers for their detailed and constructive suggestions.

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