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Ecological network analysis of growing tomatoes in an urban rooftop greenhouse

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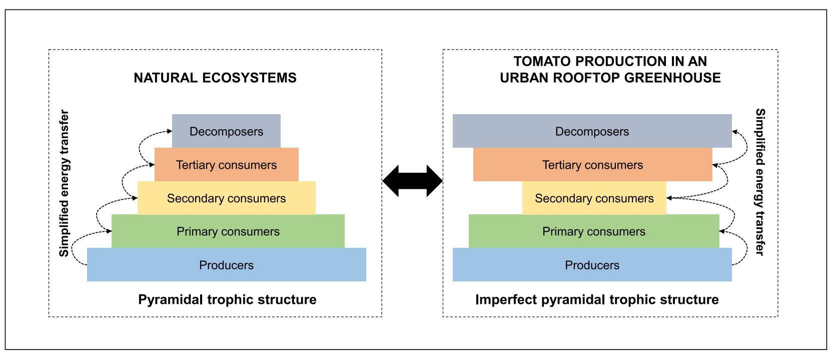
HIGHLIGHTS

- The energy-food nexus in urban agriculture was studied through interindustry flows.
- We conducted an ecological network analysis using life cycle data.
- An integrated rooftop greenhouse was assessed as an innovative case study.
- The energy trophic structure does not mimic efficient natural metabolic systems.
- Energy dissipation could be improved through renewable energy.

GRAPHICAL ABSTRACT



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ABSTRACT

Urban agriculture has emerged as an alternative to conventional rural agriculture seeking to foster a sustainable circular economy in cities. When considering the feasibility of urban agriculture and planning for the future of food production and energy, it is important to understand the relationships between energy flows throughout the system, identify their strengths and weaknesses, and make suggestions to optimize the system. To address this need, we analyzed the energy flows for growing tomatoes at a rooftop greenhouse (RTG). We used life cycle assessment (LCA) to identify the flows within the supply chain. We further analyzed these flows using ecological network analysis (ENA), which allowed a comparison of the industrial system to natural systems. Going beyond LCA, ENA also allowed us to focus more on the relationships between components. Similar to existing ENA studies on urban metabolism, our results showed that the RTG does not mimic the perfect pyramidal structure found in natural ecosystems due to the system's dependency on fossil fuels throughout the supply chain and each industry's significant impact on wasted energy. However, it was discovered that the RTG has strong foundational relationships in its industries, demonstrating overall positive utility; this foundation can be improved by using more renewable energy and increasing the recycling rates throughout the supply chain, which will in turn improve the hierarchy of energy flows and overall energy consumption performance of the system.

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1. Introduction

The rising demand for food and energy in cities puts increasing pressure on our existing production systems. Currently, 50% of the people live in cities, but these areas are expected to host up to 66% of the world population by 2050 (United Nations, 2015). Feeding this population will be very energy intensive. About 40% of the world's energy is used by the agri-food sector (Food and Agriculture Organization of the United Nations (FAO), 2011). With increasing demand for both food and energy in urban areas, it will be increasingly important to optimize the energy used in producing food. The current food production system has a high consumption of energy resources throughout its life cycle; hence, this issue should be addressed in sustainable urban modeling of the future (European Environment Agency, 2010).

Urban agriculture is a possible solution to address the increasing food and energy demand in cities and is one of the initiatives that cities worldwide include in their circular economy action plans (Petit-Boix and Leipold, 2018). While urban agriculture can take different forms (e.g., community gardens or vertical farms), rooftop gardening has received great attention in the literature and in practice as a viable option for partially meeting the vegetable needs and promoting the self-sufficiency of urbanized regions (Astee and Kishnani, 2010; Goldstein et al., 2016; Orsini et al., 2014; Pons et al., 2015; Saha and Eckelman, 2017). For instance, rooftop greenhouses (RTGs) offer environmental benefits by reducing the transportation needed to move food into the cities and by optimizing water management through rainwater and greywater use (Cerón-Palma et al., 2012). Buildings with plants on roofs use less energy (Eumorfopoulou and Aravantinos, 1998; Wong et al., 2003), which correlates with economic savings (Castleton et al., 2010; Kosareo and Ries, 2007). When the entire supply chain of tomato production is considered, an RTG can reduce the energy demand of the system by 74% compared to conventional linear production (Sanyé-Mengual et al., 2013). Additionally, using a rooftop for food production maximizes usable surface area of a building and increases profitability (Cerón-Palma et al., 2012). Socially, RTGs bring food closer to consumers, which results in short and direct producer-consumer relations, allowing for fresher, locally produced food. RTGs also have the potential to create jobs and social cohesion (Cerón-Palma et al., 2012; Kingsley and Townsend, 2006; Wallgren and Höjer, 2009).

To realize the promise of RTGs as a sustainable and circular solution for urban food production, we need insight on the structure and the interactions of the system components. Understanding the relationships among energy flows within the food system is essential to reduce the energy impacts of food production. The primary tools involved in this assessment have traditionally been life cycle assessment (LCA) and input-output (IO) tables, which have been widely applied to agricultural systems (e.g., Hatirli et al. (2005), Ozkan et al. (2004) and Roy et al. (2009)). These tools provide a good basis of inputs and outputs and, in particular, the energy flows in technological systems but they do not consider in detail the relationships among indirect interactions or indirect flows of energy within the system. Given the complexity of life-cycle inventories, addressing their network interactions through additional tools, such as ecological network analysis (ENA), might help identify elements in the network's structure that support sustainability in supply chains (Navarrete-Gutiérrez et al., 2016). In fact, ENA has already been applied in cities to study a variety of interactions among urban flows, including monetary transactions (Tan et al., 2018), energy (Fath et al., 2010), water (Zhang et al., 2010), and carbon flows (Chen et al., 2018; Chen and Chen, 2012). In the case of urban agriculture, this type of analysis remains unexplored.

We aim to address this literature gap by using ENA to provide richer details on the relationships of the energy flows within the food system. We focused on an existing RTG that was previously analyzed from an LCA lens. With ENA, we made an analogy to ecosystems and identified the 'trophic levels' ('who eats whom') within the technological system. We also used ENA tools to determine the symbiotic, control, and dependence relationships among system components.

2. Materials and methods

2.1. Steps for adapting ecological network analysis to engineered systems

ENA was first proposed by Patten (1978) to model natural ecosystems. It was derived from an economic IO analysis (Leontief, 1951) to study the structure and function of different members of an ecosystem. Since the first propositions made by Patten (1978) and Finn (1978), the ENA methodology has evolved and additional analyses were added to the model (Fath, 2007; Fath and Patten, 1998; Matamba et al., 2009; Patten, 1991). More recently, this method has been used in modeling hybrid socioeconomic and ecological systems from IO data (Li et al., 2018; Liang et al., 2018; Schaubroeck et al., 2012) and a few studies adapted ENA to engineered systems (Lu et al., 2015; Navarrete-Gutiérrez et al., 2016; Pizzol et al., 2013; Schaubroeck et al., 2012; Yang and Chen, 2016). Our approach builds upon this work with a focus on LCA data.

Our adaptation of ENA to urban agriculture included seven steps (Fig. 1). The first three steps were taken from conventional LCA modeling (ISO, 2006). In goal and scope (step 1), the functional unit and system boundaries of the system were defined. In the life cycle inventory (LCI) (step 2), the material and energy flows were quantified from unit or aggregated processes. In the life cycle impact assessment (LCIA) (step 3), the LCI is generally translated into specific environmental indicators (e.g., primary energy demand (PED), global warming, resource depletion, toxicity, etc.). In LCA, modeling multiple impact categories is important to avoid burden shifting from one impact to another. However, in ENA the inter-compartmental flows are modeled using only one unit of currency (Fath, 2007). Examples include currencies based on energy, carbon or water flows (Fang and Chen, 2015; Lu et al., 2015; Mao and Yang, 2012; Schaubroeck et al., 2012; Yang and Chen, 2016; Yang et al., 2012; Zhang et al., 2010). In this study, we focused on the PED indicator, which is an appropriate currency for illustrating the interactions of the food-energy nexus.

In transitioning from LCA to ENA, the LCA data were disaggregated into the compartments to be used in ENA. LCA data should ideally be balanced in material and energy flows but this is often not the case when large systems are analyzed. In addition, disaggregation, which can change the conceptual description of the system, can result in unbalanced material and energy flows. In our study, we did not find unbalanced flows to be a major problem. We tracked LCI flows throughout the network and converted them into PED. Since we had a small number of nodes, we could manually balance the flows using an energy balance based on the aggregation of materials between compartments. Other methods (Ulanowicz, 2004) and dedicated software (e.g. ENA-r (Borrett and Lau, 2014) and EcoNet (Kazancı, 2007)) may be needed for balancing the flows in more complex systems.

Once the system was modeled as a balanced network of compartments and flows, ENA calculations were carried out. Our analysis included the throughflow analysis (TA), network utility analysis (NUA), and network control analysis (NCA). These steps were adopted from Yang and Chen (2016). It should be noted that there are multiple other calculations that can be employed in ENA; however, adaptation of these tools to engineered systems is in its infancy. Other ENA metrics that may be used in the future include the efficiency and redundancy analyses for network organization, network robustness, and indices to describe network synergy, mutualism, and diversity (Chen and Chen, 2012; Fang and Chen, 2015; Lu et al., 2015).

2.1.1. Throughflow analysis (TA) calculations

The input and output flows for each compartment and the total system throughflow (TST), which is the sum of all stock flows through the system, were calculated from Eqs. (1)–(3). The direct flow matrices

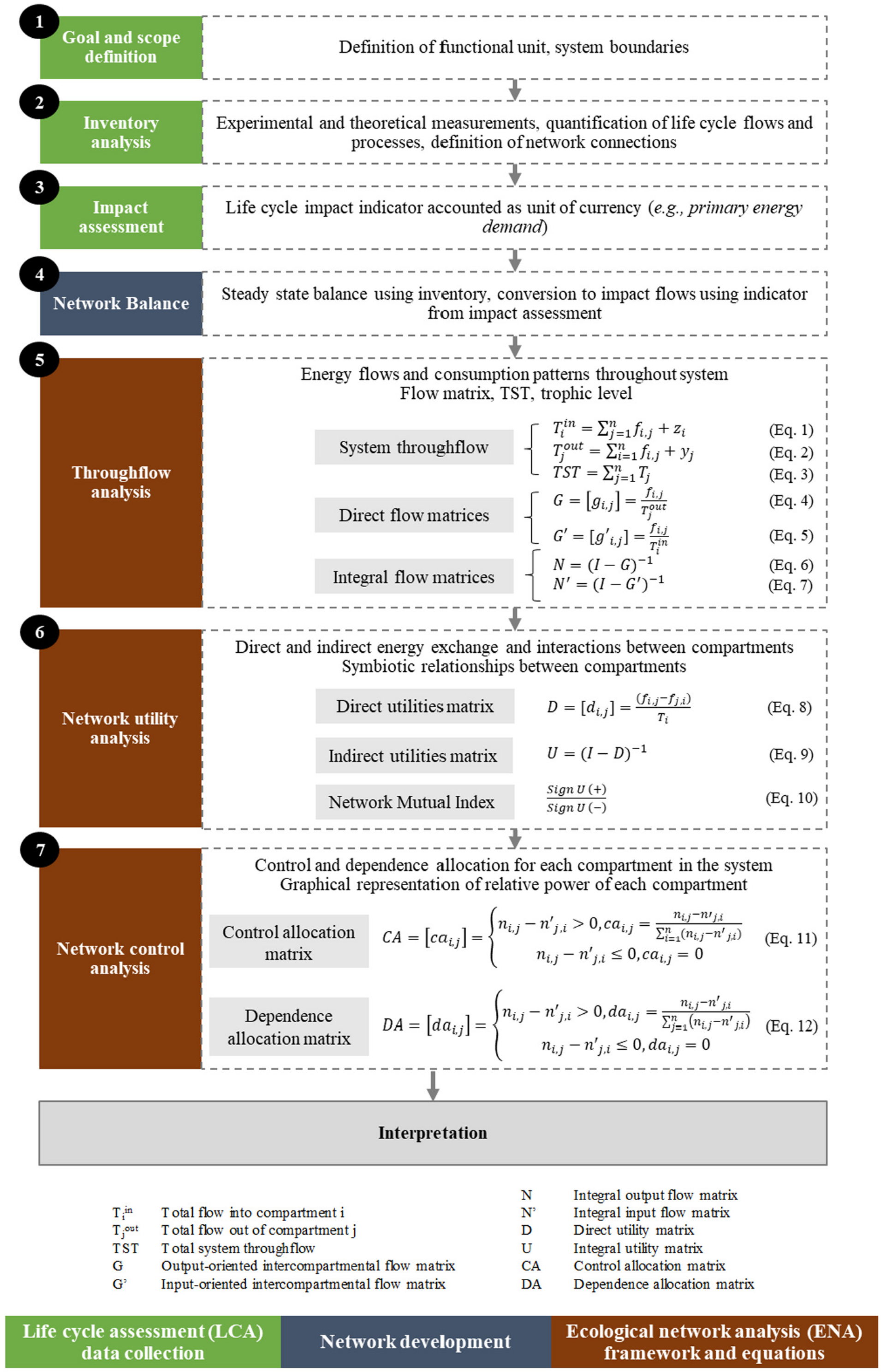

Fig. 1. The seven-step framework used in this study. LCA data and analysis are adapted to ENA in step 4. ENA tools are used in steps 5–7 to identify the trophic relationships, symbiotic relationships and control and dependence within the system.

(Eqs. (4)–(5)) were used to calculate the fraction of flows coming into the row compartment *i* from the column compartment *j* (*G*) and the fraction of flows leaving *j* that are going to *i* (*G*′). The Leontief inverse of the direct flow matrices was then used to calculate the integral flow matrices (Eqs. (6)–(7)) that represent both the direct and the indirect pathways that a stock takes through the system. Leontief inverse captures the direct (I), first tier indirect (G), second tier indirect (G^2), and all other 'n' number of indirect flows in the direct flow matrix [$(I-G)^{-1} = I + G + G^2 + G^3 + G^4 + \ldots = \sum_{n=0}^{\infty} G^n \sum_{n=0}^{\infty} G^n$]. Each power of the *G* or *G*′ matrix correlates to the flow path length between compartments. Taking the sum of each power converges to Eqs. (6) and (7).

As part of the TA, we also calculated the trophic levels by dividing each flow ($T_{i,in}$) by the TST which provided the fraction of flow that each compartment requires of the total system of energy flows that travel through all compartments. Trophic level analysis is analogous to natural systems. It allowed us to identify the function (i.e., producer, consumer, decomposer) of each compartment within the hierarchy of the urban agricultural system (Zhang et al., 2014).

2.1.2. Network utility analysis (NUA) calculations

We further analyzed the relationships among compartments using NUA. We calculated the direct utility matrix (D) to represent the exchange of materials between two compartments based on direct flows of path length one (i.e., direct connection between two compartments) (Zhang et al., 2014). The components in the matrix represented the fraction of total throughflow into compartment *i* that are associated with the stock gained or lost by compartment *i* from *j* (Eq. (8)). Following the same summation technique in Eqs. (6) and (7) with the Leontief inverse, we also calculated the integral utility matrix (U) which represented the exchange of materials between two compartments, taking into consideration all path lengths.

The signs of these matrices indicated if there is a gain or loss of materials between compartments. The sign matrix was determined for both the direct and indirect relationships between compartments. The results from the sign matrices in NUA were analyzed to describe the symbiotic relationships between compartments, defined by Yang and Chen (2016). NUA also included the network mutual index (NMI) which compared the number of positive exchanges to negative exchanges of a stock between compartments throughout the entire system (Fath and Patten, 1998). This showed if positive utility is greater than negative utility.

2.1.3. Network control analysis (NCA) calculations

To identify the influence of each compartment on another, we used NCA which included the control allocation (CA) matrix (Eq. (11)) and dependence allocation (DA) matrix (Eq. (12)) (Fig. 1). Components $ca_{i,j}$ represent the relative amount of control that compartment *j* allocates to compartment *i*, and $da_{i,j}$ represents the amount of relative dependence that compartment *i* has on compartment *j*.

2.2. Application of ENA to the life cycle inventory of an RTG

The RTG we modeled is an integrated RTG (i-RTG) of the ICTA-ICP building at the Autonomous University of Barcelona in Spain. This RTG is considered to be an i-RTG since it is symbiotic with the building, sharing resources and increasing the efficiencies of both systems (Pons et al., 2015; Sanjuan-Delmás et al., 2018b). All data we used for this paper were taken from a theoretical analysis conducted by Sanyé-Mengual et al. (2015), where details of the system and the LCA model are described. The i-RTG is housed in a six-floor building and occupies 900 m^2 of space on the roof that is used as a harvesting surface. The functional unit is 1 kg of beef tomatoes grown in a hydroponic system, where the yield is assumed to be 25 kg of tomatoes per square meter. The system boundary definition was also taken from Sanyé-Mengual et al. (2015), where the greenhouse structure was assessed from cradle to grave and the tomato production, from cradle to farm gate (Fig. 2). The i-RTG has a lifespan of 50 years. The compartments we created for the ENA match the system processes described in Sanyé-Mengual et al. (2015) (Table 1). Yet, we assumed that the tomatoes were consumed in the building, excluding packaging and transport to other consumption points. Any flows related to consumption (i.e., tomato processing or food waste) were excluded from the analysis. The inventory data are further described in Table S1 of the Supporting Information. In addition, we added three new compartments to provide additional insight: fossil fuels, renewable energy, and dissipation. Background LCI data for each process and material were retrieved from the GaBi 6 Professional database (Thinkstep, 2016). From GaBi, we calculated the primary energy demand (PED) (in MJ) as an indicator of the energy flows between compartments. Dissipation was calculated as the difference between the net and gross calorific value obtained for each material and process. This value represents the energy that is not consumed in system processes. Fossil fuels and renewable energy contribution to each process was defined from the disaggregated PED indicators obtained through GaBi at the LCIA stage. All energy inputs to the system were classified as either fossil fuels or renewable energy. These inputs were considered as the primary energy of the system that flows through system processes and is stored in materials as embedded energy. This allowed for the calculations to account for and describe the interactions each compartment has with fossil fuels and renewable energy.

3. Results

3.1. Energy flows within the i-RTG's supply chain

After disaggregating the life-cycle data to create a network of energy flows, we were able to identify the trophic structure of the RTG supply chain (Fig. 3). Considering the sequence of connections between compartments, the trophic levels correspond with the life cycle stages of the system. The producers are fossil fuels and renewable energy, which supply all the energy needed for the processes in the system. The primary consumers are manufacturing and the power grid, which provide more direct and embodied energy that is needed for the secondary consumers, construction and maintenance. The embodied energy from construction and maintenance then flows to the tertiary consumer, production, along with some energy from the primary consumers. The production sector provides embodied energy to the waste management sector and wasted direct energy to the dissipation sector. Waste management and dissipation are the decomposers of the system,

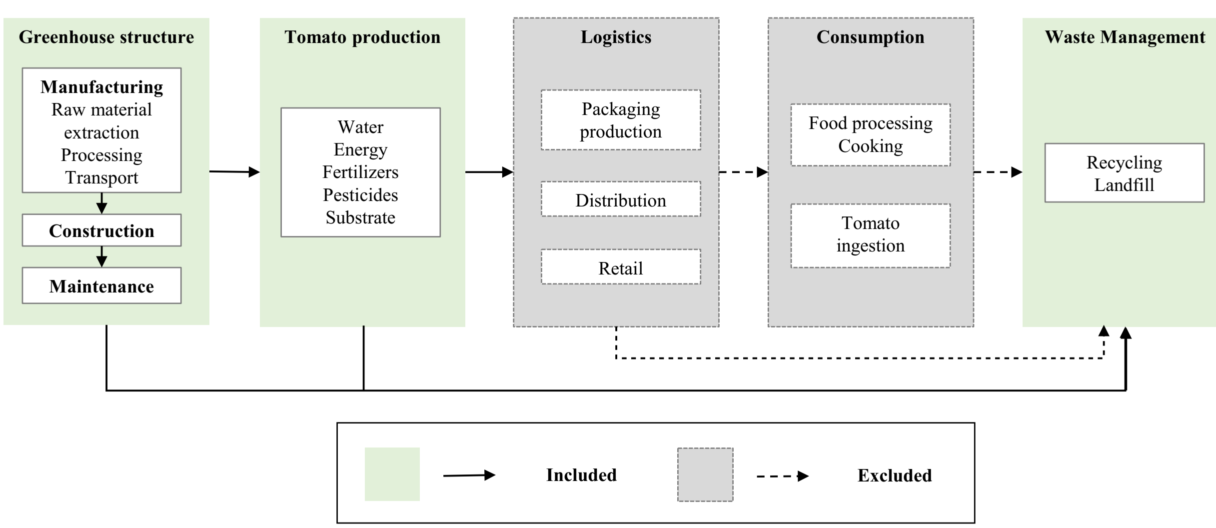

Fig. 2. System boundaries considered in the LCA of the i-RTG adapted from Sanyé-Mengual et al. (2015).

Table 1
Description of compartments used in the ENA.

Compartment	Acronym	Elements included in the energetic assessment
Fossil Fuels	FF	All nonrenewable energy used for each process, including diesel in transportation
Renewable Energy	RENEW	All forms of renewable energy used for each process
Manufacturing	MAN	Extraction and processing of materials used in the i-RTG
Power Grid	POWER	Electricity from the power grid (2014)
Construction	CONSTR	Building of the greenhouse structure
Maintenance	MAINT	Maintenance needed for the greenhouse structure
Production	PROD	Processes and materials required for producing tomatoes including water, electricity, fertilizers, pesticides, and substrate
Waste Management	WASTE	Waste treatment of all materials used in the system, including recycling of steel
Dissipation	DISS	The difference between gross PED and net PED that is dissipated from each process

returning both the embodied material and wasted energy to the external environment. Waste management also attributes a flow back to manufacturing which represents the recycled materials that were used in the system. This embodied energy is shown as an output from manufacturing to the external environment to account for the reusability of these materials (Yang and Chen, 2016).

In terms of energy flows, the TA showed a total energy input of 5.26 MJ/kg (Fig. 3), which was reasonably close to the cumulative energy demand (3.25 MJ/kg) reported by Sanyé-Mengual et al. (2015). The two numbers do not completely match because we used the GaBi software and databases instead of SimaPro and ecoinvent and it is likely that we might have selected slightly different processes in our LCI as we re-created Sanyé-Mengual et al.'s (2015) LCA. We found manufacturing to be the main consumer of fossil fuels, representing 69% of the net energy input. This result is also consistent with the theoretical LCA results found in Sanyé-Mengual et al. (2015), where the steel structure of the greenhouse was the main contributor to the environmental impacts due to an oversized design complying with security standards (Sanjuan-Delmás et al., 2018b). These values will be highly dependent on the location of the RTG, as the country's electricity mix will determine the sources of energy production. After adding up all of the flow interactions through the square matrix (Table S2 of the Supporting Information), the total system throughflow (TST) was found to be 21.6 MJ. This value is not to be compared with the PED reported in conventional LCAs, as interactions between compartments entail a transfer of energy even if this is not being consumed in the receiving compartment itself. As a result, accounting for energy flows through interactions produces a double-counting effect. This initial throughflow perspective in ENA, however, lays the foundation for conducting further steps of the analysis. Many of the subsequent ENA calculations, including the trophic level analysis, are derived from the original flows and the compartments' system throughflow.

Based on the TA and the composition of the trophic levels, we studied the trophic structure of the system in terms of energy. A longstanding concept in ecosystems ecology, the trophic chain is generally described as a pyramidal structure. The pyramidal structure can be considered as an ideal pattern of energy flows, since it is what the natural world has proven to be the most sustainable throughout history, which provides insight on the performance of energy flows in an urban agriculture system. This is due to the 10% rule in ecology, which defines that only 10% of all the energy from a lower trophic level is

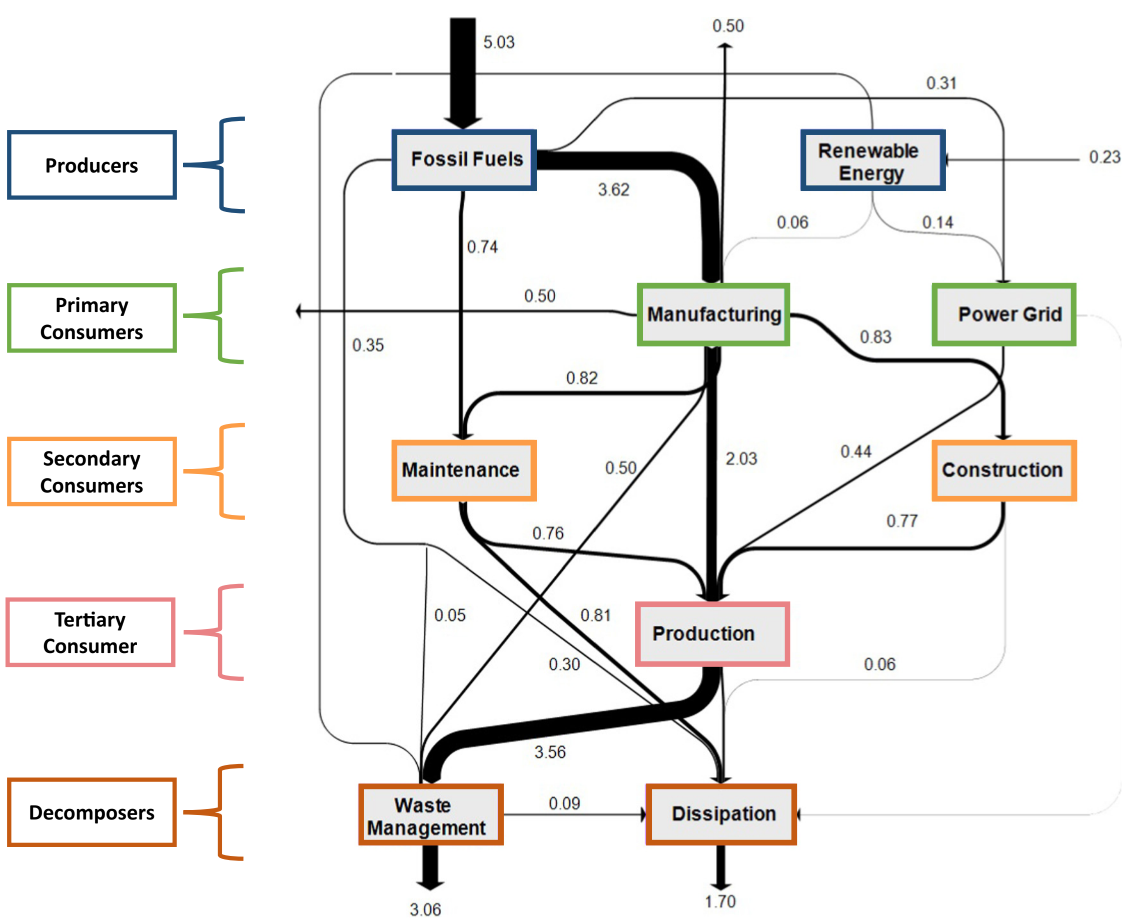

Fig. 3. Energy flows (in MJ) in the supply chain of the i-RTG. Data per functional unit (1 kg of tomato).

typically transferred to the next trophic level because the other 90% of energy is used for metabolic processes, or lost as heat (Lindeman, 1942). Since less and less energy is available for consumption of organisms in a higher trophic level, the result is a pyramidal structure, and it has proven sustainable in most ecosystems.

The trophic energy levels for this urban agriculture system did not mimic the pyramidal trophic structure found in natural processes (Fig. 4). From producers to secondary consumers, the structure resembles the expected pyramidal shape resulting from natural ecosystems. However, the tertiary consumer involves the third largest amount of the TST (18%). In this stage, the production compartment receives an input of electricity from the power grid along with an amount of energy embedded in fertilizers or equipment. The contribution of production to the TST will be highly affected by both the efficiency of the electric equipment used in the RTG and the country's electricity mix.

In addition to production, waste management from the decomposers of the system requires a large amount of the TST (17%), causing an imperfect pyramidal trophic representation. Decomposers have an important role to use remaining energy and maximize the energy throughflow and cycling in an urban metabolic system, just as they do in nature (Fath et al., 2010). However, in this system, a large amount of materials were assumed to be disposed of in a landfill, which does not enable the desired cyclical role of decomposers in the network and will inevitably result in a loss of energy and resources at the end of the i-RTG's life cycle. With a large portion of the energy in the i-RTG flowing into this ineffective system decomposer, the overall system will not be able to sustain itself like a natural system. This suggests that the current energy flows in the system are not well developed and need to be improved upon for consistent sustainability and resilience. This could be more closely achieved by increasing the recycling rates of the system components.

The results of ENA studies on urban metabolic processes commonly result in imperfect pyramid structures. For example, Lu et al. (2015) modeled carbon flows for an eco-industrial park, which resulted in the secondary consumers showing the most prominence in the trophic relationship. An imperfect pyramid was also seen in Fath et al. (2010) in modeling the energy flows of four Chinese cities. In ENA studies, this is typically indicative of an unharmonious relationship of stock flows. However, in some natural ecosystems where the upper trophic levels do not have enough prey in the trophic level beneath them to satisfy their energy needs, the higher trophic level consumers can still thrive by preying on even lower trophic levels that have an excess of organisms for energy consumption (Trebilco et al., 2013). This is the consumption pattern that the i-RTG system exemplifies with production, a tertiary consumer, receiving energy from the power grid, a primary consumer. Although this is not the ideal pattern of energy consumption, it is feasible for a system to succeed by doing so. At the same time, for prolonged sustainability, a pyramidal trophic structure is desired. As compared to a natural ecosystem, an industrial ecosystem inhibits a similar trophic structure but lacks the direct decomposition which

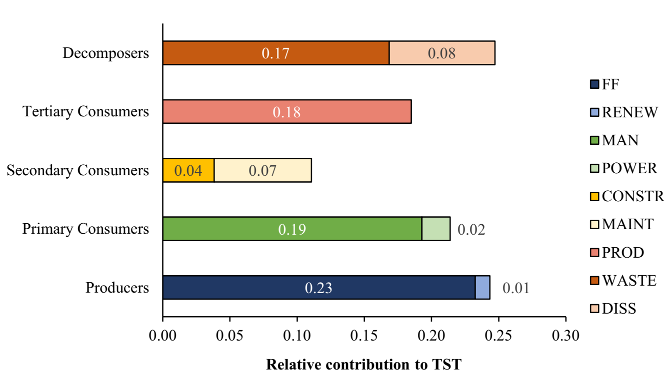

Fig. 4. Trophic energy levels and percentages of the TST for the i-RTG system.

cycles back into the initial inputs. Because of the preliminary boundaries of the industrial system, the effects of recycling cannot be directly considered in some cases. This is why in natural ecosystems the trophic structure is often a more balanced pyramid while industrial systems may exhibit imperfect hierarchies within their trophic structures.

3.2. Relationships in the supply chain

NUA, the second step of ENA, gives insight into the overall extent of the interactions between compartments in the system. The detailed SignD/SignU matrix is provided in Table S3 of the Supporting Information. In the direct flow matrix D, 28% of the interactions between the number of compartments result in a loss of energy, and 28% of the number of interactions result in a gain of energy. In other words, these interactions increased the receiving compartments' energy stock. Adversely, donor compartments of these interactions lost energy stock. Since the D matrix only considers direct flows, it provides a give-and-take relationship for the pairwise compartments, so it makes sense that the number of gains and losses in this calculation are equal when mass and energy balances are maintained. However, the most useful information from here is that with 28% of interactions gaining energy, and another 28% losing energy, there is 43% of intercompartmental pairs that do not have energy flows among them. In other words, there is no interaction or exchange of energy among 43% of the possible pairs.

However, when considering the indirect flows in the integral flow matrix, U, 35% of energy exchanges between compartments are negative, 58% are positive, and only 7% do not exchange energy. The difference in these results shows the significance of considering the indirect flows and transfers in a system. The U matrix considers the exchange of materials between compartments when taking into account the flows that passed through other compartments before reaching the destination. There are many interactions that show no direct exchange of energy (43%) in the D matrix; however, when considering all of the system processes and energy cycling through the system in total, many of the compartments showing no interaction actually reveal some type of energy exchange, dropping the percent of compartments with no interaction much lower (7%).

A comparison between pairwise compartments in each SignD and SignU reveals the symbiotic relationships between compartments, represented for the system in Fig. 5. The D matrix shows that 49% of the relationships between compartments do not exchange energy (neutral), whereas there is a resource exploitation in 51% of the cases. However, when taking into consideration the indirect energy flows in the U matrix, the results are more insightful on the overall system performance. Many of the neutral relationships are uncovered to show other symbiotic relationships. 59% of the neutral intercompartmental relationships are actually shown to be mutualistic in the integral utility matrix. With mutualistic relationships being the most frequent change from a neutral relationship in U matrix, the other neutral relationships were shown to be 18% competitive and 18% exploitative. The remaining 5% of neutral compartments in the D matrix remained neutral in the U matrix. The percent of all the relationships in each matrix are fully described in Table S3 of the Supporting Information. This reiterates the significance of considering the indirect energy flows with a pathlength greater than one. In fact, the indirect flows in a system have been recognized as a crucial aspect to the function in a system, oftentimes having a greater influence on a system than its direct flows (Krivtsov, 2004; Patten and Higashi, 1984). Overall, it is generally more beneficial to have strong indirect flows in a network because it offers more alternative paths for energy in the system and contributes to resilience in case one compartment fails.

With the Sign(U) matrix, the network mutual index (NMI) can be found using Eq. (10). For this i-RTG system, the NMI was found to be 1.68, which reveals there are more qualitatively positive exchanges of energy than negative exchanges of energy throughout the whole system. Contrary to the trophic level results, these values are closer to

Sign	Relationship	% of Total Relationships	
		D Matrix	U Matrix
+/+	Mutualism	-	40
+/0	Comensalism	-	5
0/+	Commensal Host	-	0
0/0	Neutralism	49	2
0/-	Amensalism	-	2
-/0	Amensal Host	-	2
-/+	Exploited	7	9
+/-	Exploitation	44	31
-/-	Competition	-	9

	FF	RENEW	MAN	POWER	CON	MAINT	PROD	WASTE	DISS
FF	0/0								
RENEW	0/0	0/0							
MAN	-/+	-/+	0/0						
POWER	+/-	+/-	0/0	0/0					
CON	+/-	0/0	+/-	+/-	0/0				
MAINT	+/-	0/0	+/-	0/0	0/0	0/0			
PROD	0/0	0/0	+/-	+/-	+/-	+/-	0/0		
WASTE	+/-	+/-	-/+	0/0	0/0	0/0	+/-	0/0	
DISS	+/-	0/0	0/0	+/-	+/-	+/-	+/-	+/-	0/0

	FF	RENEW	MAN	POWER	CON	MAINT	PROD	WASTE	DISS
FF	+/+								
RENEW	-/-	+/+							
MAN	-/+	+/0	+/+						
POWER	+/-	+/-	-/-	+/+					
CON	+/+	-/+	+/-	-/+	+/+				
MAINT	+/-	-/+	+/-	-/-	-/-	+/+			
PROD	+/+	+/+	+/0	+/+	+/-	0/-	+/+		
WASTE	+/-	+/-	+/+	+/-	+/+	+/+	+/-	+/+	
DISS	+/-	0/0	+/+	-/0	+/+	+/-	+/-	+/-	+/+

Fig. 5. Sign(D) (top) and Sign(U) (bottom) intercompartmental symbiotic relationships.

natural ecosystem behavior, as mutualism is favored in natural self-sustaining systems. This is beneficial in an i-RTG system because it shows that the industries are cooperating in a way that more industries benefit by receiving energy than are harmed by losing energy, which is a good foundational relationship to improve the system upon.

3.3. Control and dependence of the system compartments

The CA matrix shows that waste management and dissipation are controlled by all sectors (Fig. 6). 100% of waste management's control in the system is on the dissipation compartment, or what is wasted. In addition, the production compartment has the largest control allocated to waste management (85%). Most compartments also exert between 24% and 47% control over production.

However, renewable energy has the lowest control on dissipation (6%), compared to the other sectors. For renewable energy, this control is due to the indirect dissipation that is observed when using renewable energy in the power grid. The energy from the power grid in this study was eventually dissipated, which is why renewable energy shows any control on the dissipation compartment. However, in the original GaBi data, it was shown that there was no direct energy loss at all from the processes using renewable energy. On the contrary, fossil fuels contribute energy to dissipation in each process it is involved. This indicates that the 11% allocation fossil fuels have on dissipation is more likely influenced by the direct use of nonrenewable energy sources, rather than a result of losing energy to processes that consume and then dissipate fossil fuels, as described by renewable energy in the power grid.

The control analysis gives an informal insight on the i-RTG system efficiency. When the indirect energy flows are considered throughout the supply chain, every industry transfers energy to the environment through the dissipation and waste management compartments. For many of the system's industries, the largest control is allocated towards waste management, showing that they lose more energy to the environment rather than cycling through the system and exchanging energy with the other industries. This implies that the system's efficiency could be improved by collecting and reusing the wasted energy for other system processes. Since renewable energy shows the lowest control on dissipation, it is reasonable to suggest that using more renewable energy sources throughout the supply chain will improve the amount of energy lost to dissipation in the system. System efficiency could also be improved with more recycled materials and better waste management practices. In the system, a small amount of steel is recycled, which is indicated in this analysis with a flow from waste management to manufacturing. Here, the control allocation indicates that this reuse of material accounts for a negligible degree of waste management's control on the system. Rather, waste management has 100% control on dissipation, showing that the decomposers of the system are not effective at returning energy or materials back into system processes.

The DA matrix shows that fossil fuel and renewable energy are not dependent on any of the other sectors as producers. Manufacturing, a primary consumer, is 61% dependent on fossil fuels and only 29% dependent on renewable energy. The secondary consumers, construction and maintenance, are primarily dependent on manufacturing (42% and 32%, respectively) and fossil fuels (35% and 51%, respectively). Since manufacturing carries a large dependence on fossil fuels, these compartments collectively require a large amount of fossil fuels. The power grid is the only compartment which has a significantly higher dependence on renewable energy than fossil fuels. In turn, the compartments with a considerable dependence on the power grid (production and waste management) are each slightly more dependent on renewable energy than fossil fuels.

4. Discussion

Using ENA to understand the food-energy nexus of an RTG from a life-cycle approach provides additional information that LCA alone did not unveil in previous RTG studies (Sanjuan-Delmás et al., 2018a; Sanyé-Mengual et al., 2015). This approach not only uncovers where in a system critical issues are to be found, but it also answers the question of how the system works based on the relationships among compartments. Here, we showed the connections among the compartments involved in the production of 1 kg of tomatoes in an RTG. Not surprisingly, the system largely depends on fossil fuels because 21% of the electricity demand coverage consists of nuclear power (Red Eléctrica de España, 2014). This conclusion could already be drawn with LCA, but ENA helped us determine the structure of the system. We found that industries have strong, mutualistic relationships that build a sustainable foundation to be built from. However, each industry

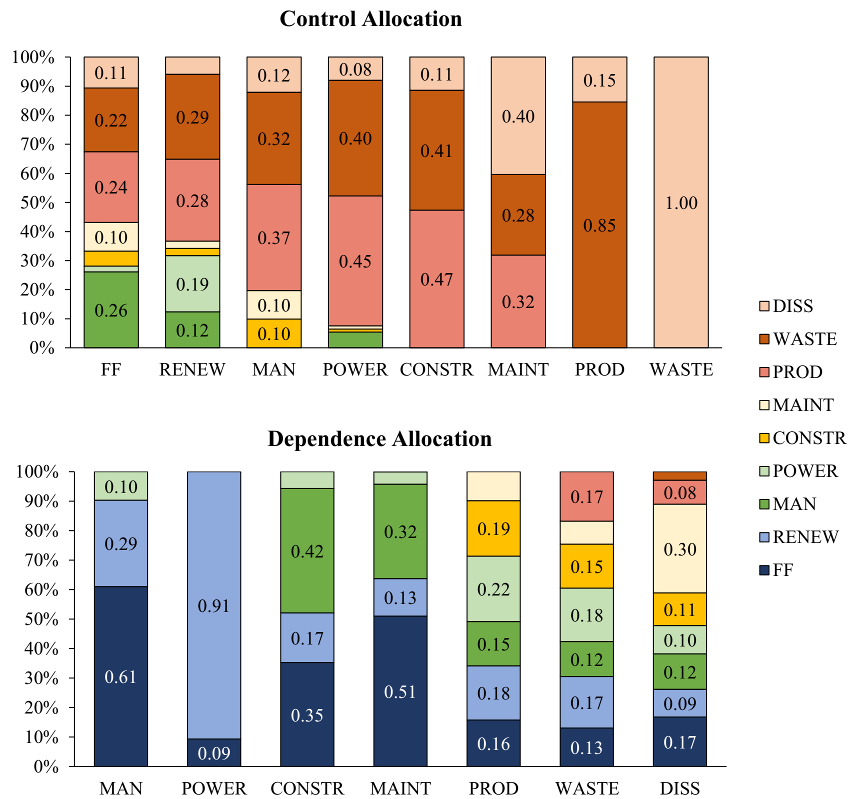

Fig. 6. Control and dependence allocation for each industry in the i-RTG system.

is significantly contributing to the waste management and dissipation sectors throughout the supply chain. This indicates that there is poor cycling throughout the system, with the majority of compartments transfering a significant amount of energy to the environment. The decomposers of the system are thus ineffective. If more of this energy were able to flow to a different, more effective decomposer, the system would better be able to return the energy to its own environment and continue decomposing and recycling the energy, much like how a natural ecosystem cycles energy. The large contribution of each industry to dissipation can be seen as a result of the supply chain's dependency on fossil fuels, since eventually all nonrenewable energy was dissipated.

One of the recommendations arising from the analysis is that, for RTGs to become more circular and sustainable, there is a need to (i) increase the share of renewables and (ii) increase the recycling rates. Both strategies will reduce the dependency on fossil fuels, with renewable energy acting less strongly on the dissipation of useful energy throughout the life cycle. This might imply a relative increase in the energy efficiency of the overall system. Recycling not only increases the material availability within the system but also reduces the need for external energy inputs. Decomposers (e.g., waste valorization facilities) would demand some additional energy to run their metabolic processes, but cycling this energy back might be beneficial to improve the trophic structure. In the context of circular economy research, assessing these strategies from an ENA standpoint is highly encouraged to test whether energy would be positively redistributed within the network.

Another aspect to consider is the integration of the RTG into urban environments. Given that some energy is currently being dissipated/ wasted, RTGs could balance these losses by providing a service to other systems that demand energy. For instance, it has been shown that RTGs and green roofs result in significant energy savings for the building and help regulate the building temperature (Eumorfopoulou and Aravantinos, 1998; Wong et al., 2003), which relates to economic savings in heating and cooling the building (Castleton et al., 2010; Kosareo and Ries, 2007). The i-RTG under analysis interacts with the building it is located on and recycles waste thermal energy from the building to grow vegetables (Nadal et al., 2017). This consideration is beyond the system boundaries of our study because we did not consider the life cycle impacts of the entire building, which do not apply to the greenhouse function itself. In this case, the dissipation compartment as a decomposer is not effective in recycling energy back into the i-RTG system itself, but the i-RTG is in fact providing benefits beyond the system boundaries.

5. Conclusions

This ENA of an i-RTG system helped us identify the energy structure of an urban agricultural setting. Our results showed that the RTG does not mimic the perfect pyramidal structure found in natural ecosystems due to the system's dependency on fossil fuels throughout the supply chain and each industry's significant impact on dissipated and wasted energy. However, it was discovered that the system has strong foundational relationships in its industries, demonstrating overall positive utility; this foundation can be improved by using more renewable energy and increasing the efficiency of energy use throughout the supply chain, which will in turn improve the hierarchy of energy flows and overall energy consumption performance of the system.

These results can not only be used to make improvements on the system but also to predict future behaviors. Based on the relationships between compartments, scenarios could determine to what extent variations in a particular compartment will affect the other compartments it interacts with. Our first conclusion points to an increased use of renewable energy to reduce dissipation and increased recycling rates for cycling energy back into the system. Additionally, we call for a better integration of urban agriculture, in general, and RTGs, in particular, into the planning of sustainable circular cities. Taking stock of the existing network of industries involved in the energy structure of this food system might help to identify additional hotspots for cities to consider when closing resource loops.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.09.293.

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