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Structuring an integrated water-energy-food nexus assessment of a local wind energy desalination system for irrigation

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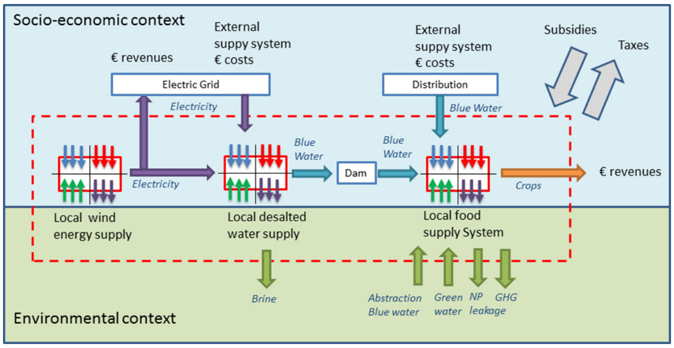
HIGHLIGHTS

- A novel approach for integrated assessment of water-energy-food systems is provided.
- It is validated for a local desalination system in the drought-prone Canary Islands.
- The system uses wind energy to provide desalted water for agriculture.
- Inputs, outputs and wastes are assesses in biophysical and economic terms.
- Trade-offs across different levels and dimensions of analysis can be anticipated.

GRAPHICAL ABSTRACT



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ABSTRACT

Desalination is increasingly put forward as a sustainable local solution to water scarcity in combination with the exploitation of renewable energy sources. However, the complexity of the resource nexus entails the unavoidable existence of pros and cons across its various dimensions that can only be assessed at different scales of analysis. In turn, these pros and cons entail different winners and losers among the different social actors linked through the nexus. To address these challenges, a novel approach to resource nexus assessment is put forward, based on multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) and recognizing the resource nexus as a wicked problem. The integrated representation identifies the existence of biophysical constraints determined by processes both under human control (in the technosphere) and beyond human control (in the biosphere). The approach is illustrated with a local case study of desalination in the Canary Islands, Spain. The material presented has been generated in the context of the project "Moving towards adaptive governance in complexity: Informing nexus security" (MAGIC) for use in participatory processes of co-production of knowledge claims about desalination, a prerequisite for informed policy deliberation.

1. Introduction

Desalination is increasingly put forward as a sustainable local (decentralized) solution to water scarcity, notably in combination

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with the exploitation of renewable energy sources (RES), such as wind and solar energy (Alkaisi et al., 2017; Chandrashekara and Yadav, 2017; Fornarelli et al., 2018; Gold and Webber, 2015; Gude, 2016; Manju and Sagar, 2017; Shahzad et al., 2017). However, while desalination can certainly be an essential option for resource security purposes in isolated and islands areas, an effective assessment of the performance of desalination in relation to nexus security requires a comprehensive understanding of the nature of the entanglement over water, energy, and food flows. Literature on the water-energy-food (WEF) nexus shows a general consensus on the urgent need to improve both: (i) the effectiveness of scientific analysis in integrating quantitative analyses across different dimensions and scales; and (ii) the process of governance across the existing 'institutional silos' dealing with water, energy and food separately (Al-Saidi and Elagib, 2017; Bazilian et al., 2011; Biggs et al., 2015; Cairns and Krzywoszynska, 2016; Endo et al., 2017; Garcia and You, 2016; Gulati et al., 2013; Hák et al., 2016; Hoff, 2011; Howarth and Monasterolo, 2016; Howells et al., 2013; Khan et al., 2017; Leese and Meisch, 2015; Mohtar and Lawford, 2016; Pittock et al., 2015; Rasul, 2016; Ringler et al., 2013; Verhoeven, 2015). Hence, there is the need to improve the process of generation and use of scientific information relative to the nexus. In particular, it is essential to integrate the information about two different types of trade-offs: (i) between the ecological and socio-economic side; and (ii) within the socio-economic process among different social actors, both within—e.g., producers and consumers—and across hierarchical levels—e.g., administrators and tax-payers.

The study presented in this paper has been developed within the context of the Horizon2020 project "Moving towards adaptive governance in complexity: Informing nexus security" (MAGIC). It addresses three systemic problems in WEF nexus research:

1. It is difficult to use scientific information on the nexus in participatory processes because of the nexus being a 'wicked problem' (Rittel and Webber, 1973); a problem impossible to simplify without losing relevant information. Indeed, the analysis of the resource nexus is extremely complex and requires the consideration of many factors and functional elements operating at different scales. This makes it impossible to adopt simple standard models (of the type 'one size fits all') that identify 'optimal' solutions and eliminate uncertainty from the results. The quantitative analysis of the nexus is incompatible with the paradigm of reductionism that currently dominates the generation of quantitative information. When dealing with the nexus things are not simply 'black' or 'white', costs or benefits, and quantitative results heavily depend on the assumptions made in the pre-analytical phase.
2. It is hard to generate scientific information referring to the nexus with the existing model of scientific inquiry being divided into disciplinary fields. The reductionist strategy of addressing and solving one issue at the time (using water models, energy models or food models) has created a practice of considering one data set at the time – i.e. models dealing only with water, with energy or with food. Although results of these mono-dimensional models may be contrasted with each other, the assumptions (and their credibility) underlying each one of these models are still based on the ceteris paribus hypothesis. Hence the causal relations described by the models in the different specific disciplinary domains are assumed to be independent of events that can only be observed from within a different disciplinary domain.
3. It is difficult to use scientific information referring to the nexus for governance within the actual silo structures found in existing institutions. The division into specific issues, addressed one at the time by specialized bodies, does not provide the diversity of information that would be required to gain policy relevance – i.e., who are the winners and who are the losers (at different levels of analysis) of a given policy in relation to the implications of the nexus?

The entanglement of resource flows is inherent in the complex metabolic pattern of social-ecological systems and requires a complex systems approach based on relational analysis. The current use of deterministic models trying to optimize or maximize individual objective functions in specialized governance structures simply makes the nexus invisible to the analyst. A novel approach addressing these challenges is proposed and illustrated with a case study on desalination. The rest of the paper is organized as follows. Section 2 provides a short presentation of the case study and the accounting method proposed for the analysis of the nexus across multiple scales and dimensions of analysis (MuSIASEM). Section 3 illustrates the type of results generated by the approach through a characterization of the factors determining the performance of the desalination plant in the Canary Islands. Section 4 discusses the strength and limitations of the approach (section 4). The last section concludes.

2. Materials and methods

2.1. The case study

Gran Canaria forms part of the Canary Islands, a Spanish volcanic archipelago located in front of the Moroccan coast in the Atlantic Ocean. Although the islands have diverse climatic areas and ecosystems, a subtropical climate and arid areas predominate. Indeed, the amount of precipitation in Gran Canaria is low, with an average of 300 mm per year. The porosity of the volcanic terrain further challenges storage of water in reservoirs. The monthly average wind speed at the east coast of Gran Canaria is 8.5 m/s with predominant NE direction. Strong 'trade winds' are produced between March and August (Rybar et al., 2011). Although traditionally an agricultural area, the main economic sector today is tourism. Due to population growth and the rapidly increasing demand of services for tourists, the freshwater requirement has dramatically increased (CIAGC, 2015). Underground water has traditionally been used, but depletion of water resources from the subsoil has exhausted the insular aquifers aquifers. Additionally, the overexploitation of groundwater has triggered saltwater intrusion from the sea (Instituto Tecnológico de Canarias, 2008). The underground waters of the southeastern part of the island of Gran Canaria suffer the highest degree of marine intrusion (CIAGC, 2015). Carrying freshwater from the mainland to the islands is not a viable option given the long distances and enormous costs involved, and the local government of the Canary Islands has been forced to seek alternative solutions, using alternative water sources such as desalted water.

At the east-coast of Gran Canaria island (Playa de Vargas) a seawater reverse osmosis (SWRO) desalination plant was constructed by Soslaires Canarias S.L. in 2002. It also includes water pumping, pipelines and a water reservoir. The capacity of the desalination plant (5000 m^3/day) was designed to exceed the initial water demand of crops in this area. The plant and water pumping are driven by the electrical grid but are also connected to an on-shore wind power farm (2.64 MW). The SWRO consumes energy from the electrical grid when wind power is insufficient. When the wind farm produces more electricity than needed by the SWRO, it is sold to the grid at market price (with an investment bonus of 12€ per MW).

The SWRO facility produces and sells water to local farmers. The desalted water from Soslaires Canarias S.L. irrigates up to 230 ha of agricultural crops pertaining to farmers of a local agricultural cooperative, growing mainly fresh vegetables and fruits. The water derived from the desalination plant is stored in a 2500 m^2 reservoir with a capacity of 200,000 m^3, located at 200 m above sea level. This reservoir is a strategic buffer element aimed at optimizing the wind energy used by the system by storing desalted water in periods when irrigation is not needed. Farmers in the area have the option to combine the desalted water with other water sources: groundwater and reclaimed water.

The seawater inflow happens in four catchment wells that are 50 m inland. The brine produced by the desalination plant is discharged into a specific beach-well (diluted with a concentration of between 58 and 60 g/l) that is 10 m away from the sea. The distance between the seawater catchment and brine discharge wells is sufficiently high to avoid any brine recycling into the production wells. Hydro-geological studies are done before any beach well exploration, not only to warrant the flow required but also to study underground pollution. The spatial distribution of the facilities is shown in Fig. 1.

At first glance, the Soslaires Canarias S.L. plant seems to be a perfect WEF nexus system: (1) it allows an isolated semi-arid social-ecological system to produce its own food by supplying irrigation water, (2) the supply of water is obtained from the sea, so it does not stress the exhausted aquifers, and (3) the energy for desalination is obtained from the wind, so it does not require import of fuels from outside. However, at closer look, not all the flows required and supplied by the system match each other in time.

2.2. MuSIASEM rationale

Similar to organisms, social-ecological systems (and their constituent components) must metabolize material and energy inputs to survive and evolve, thereby producing useful outputs and wastes (Giampietro et al., 2012). Using this concept of metabolism, MuSIASEM describes the functioning of social-ecological systems in terms of metabolic patterns of flow and fund elements. Flow elements describe *what the system does* in terms of metabolic activity (consumption of fuels, generation of electricity, production of crops, generation of brine), whereas fund elements describe *what the system is 'made of'* (hectares of crops, workers, wind turbines). Fund elements provide a metric to describe the size of the metabolic system. MuSIASEM differs from other approaches to 'social metabolism' in that it does not simply quantify 'flow elements', as done for example by material and energy flow analysis (MEFA) (Suh, 2005), but it relates the various flows to the specific fund elements that produce or consume them. In this way, a family of benchmarks is obtained (represented by the values of flow-fund ratios) that describes *how* the various functional elements of the social-ecological system metabolize flows. Hence, flow-fund ratios are qualitative benchmarks linked to a specific typology of functional elements. This approach was originally proposed by Georgescu-Roegen under the name of the flow-fund model (Georgescu-Roegen, 1971). For instance, the flow 'annual crop production' (measured in t) is accounted for as the product of yield (in t/ha) and land in production (in ha), but also as the product of labor productivity (in kg/h of human activity) and labor required in production (in h). In this way the system of accounting creates redundancy in the information space, which is useful for integrating information across different dimensions and scales of analysis.

One of the key features of MuSIASEM is that it provides different types of quantitative information relevant for discussing three distinct types of constraints (Giampietro et al., 2014):

(i) *Feasibility in relation to external constraints determined by processes outside of human control.* Feasibility refers to the availability of natural resources or environmental services in relation to the required supply and sink capacity (in terms of supply of required inputs and sink of wastes/emissions generated). This quantitative information is based on data referring to topography, climate, soil types, availability of renewable resources such as wind, solar radiation, water or biodiversity, and availability of non-renewable resources such as fossil energy, mineral ores. Feasibility refers to the interactions taking place between the biosphere and the technosphere.

(ii) *Viability in relation to internal constraints determined by processes under human control.* Viability concerns the nature of the internal constraints imposed on the metabolic pattern by the human socioeconomic system. This quantitative information refers to demography, labor force, productivity of economic activities, availability of technology and know-how. Viability refers to interactions taking place within the technosphere.

(iii) *Desirability in relation to normative values and institutions keeping together the social fabric.* Desirability implies the need of carrying

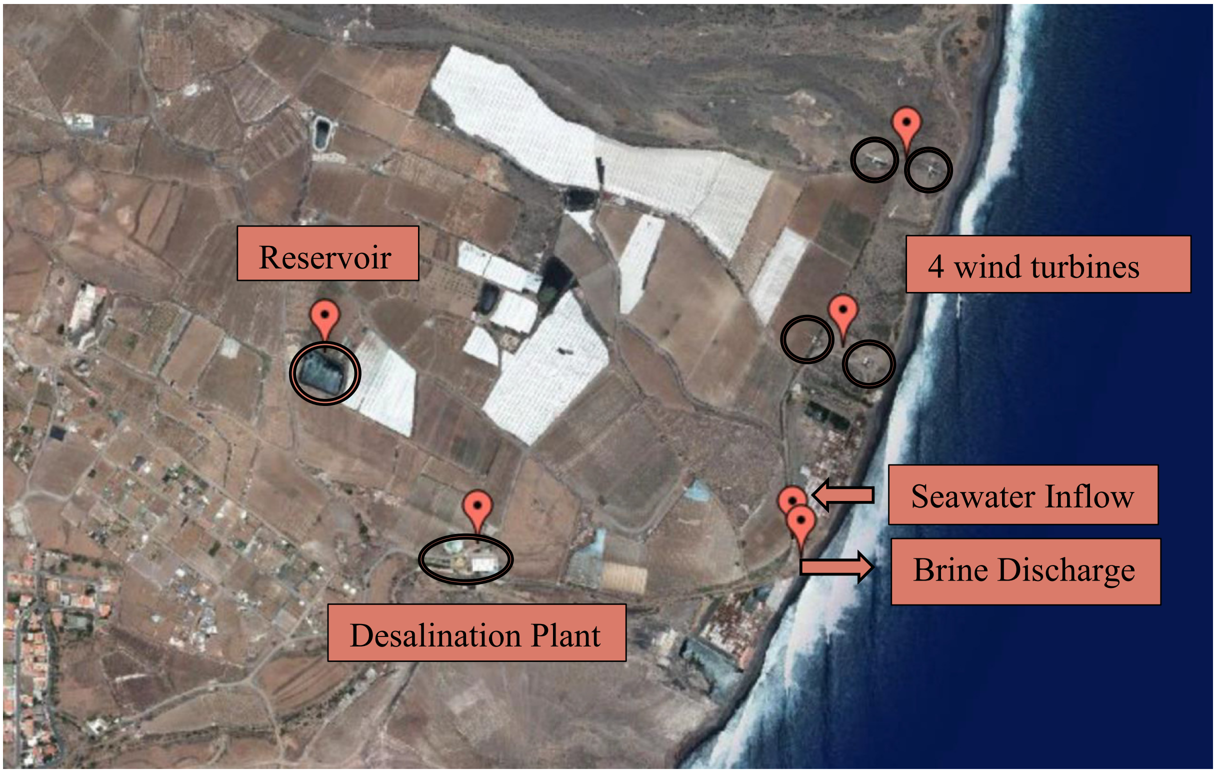

Fig. 1. Aerial view of the facilities of Soslaires Canarias S.L., scale 1:8000, standard north-up representation (IDECanarias, 2018).

out an additional check on the performance of the metabolic pattern of social-ecological systems in relation to the expectations and preferences of the social actors involved. This check cannot be based on quantitative analysis carried out by 'experts', it requires the implementation of participatory processes to involve the social actors in the integrated assessment.

MuSIASEM is based on an application of relational analysis (Louie, 2013, 2009; Rosen, 1985, 1977) to the flow-fund model of Georgescu-Roegen (1971) in three main steps: (1) identification of the hierarchical structure determining the functional relations of the metabolic elements of the social-ecological system under analysis; (2) characterization of the specific metabolic patterns of each one of the relevant functional elements using the concept of processors, and (3) generation of a series of non-equivalent representations of the metabolic performance of the WEF elements of the system considered at different levels and dimensions of analysis depending on the questions to be answered.

MuSIASEM distinguishes itself from other methods in that it is semantically open (possibility to mix semantic information to formal analysis). In the pre-analytical framing (step 1) one has to decide which metabolic elements are relevant for the definition of the hierarchical structure of functional relations. This process can be done in consultation with stakeholders. Then, in step 2, it must be decided which formal categories (associated with quantitative assessments) are needed for a meaningful characterization of the metabolic characteristics of the selected elements using the concept of processors. Finally, in the last step, the information space generated in the first two steps is used to produce non-equivalent assessments (feasibility, economic viability, technical viability, dependence on subsidies, etc.) tailored to specific research questions of interest to specific stakeholders.

2.3. The concept of processors

The concept of processor is key to MuSIASEM. First introduced by Rosen in relational analysis (Rosen, 1958), a processor is a description of the profile of inputs and outputs associated with the expression of a given process or function. An analogy of the processor is the concept of enzyme in biochemistry or the concept of production function in economics. In MuSIASEM processors represent an integrated description of the characteristics of the metabolic units of the system (González-López and Giampietro, 2017). An example of a processor characterizing the specific profiles of inputs and outputs required to carry out a particular process (task) within a multi-scale metabolic pattern is illustrated in Fig. 2. Corresponding data are stored in the form of a data array (a specific data structure).

The upper part of the processor in Fig. 2 represents the profile of internal inputs, both flows (left side, in blue) and funds (right side, in red), obtained from the socio-economic system (technosphere). Whereas flows are consumed, fund elements are not. Funds are maintained along the process (e.g., laborers, land, and machinery). They provide information about the size of the processor (in terms of hectares of land, hours of labor, or watts of power capacity).

The lower part of the processor represents the interaction with the biosphere (i.e., the environment or context of the system). It is described in terms of *external* input and output flows. On the left side, the flows directly taken from the biosphere (in green) are shown, that is, materials and energy from natural resources—the supply side of the metabolism. The lower right part (in orange) represents the output flows of unwanted by-products that are dumped in surrounding ecosystems, like wastes (brine) and emissions (CO_2)—the sink side of the metabolism.

The useful output of the processor (going into the socio-economic system) is represented by the grey arrow exiting to the right. This output represents a measurable quantity of useful product (or a mix of useful products) and corresponds to a defined amount of required flows and funds (top arrows) and a defined level of interaction with the biosphere (bottom arrows).

This structure of accounting thus provides information about: (i) inputs required/obtained from the socio-economic system (flows and funds on the top); (ii) outputs going into the socio-economic system (on the right); and (iii) inputs and outputs exchanged with the biosphere (flows on the bottom). It can be applied to a specific process

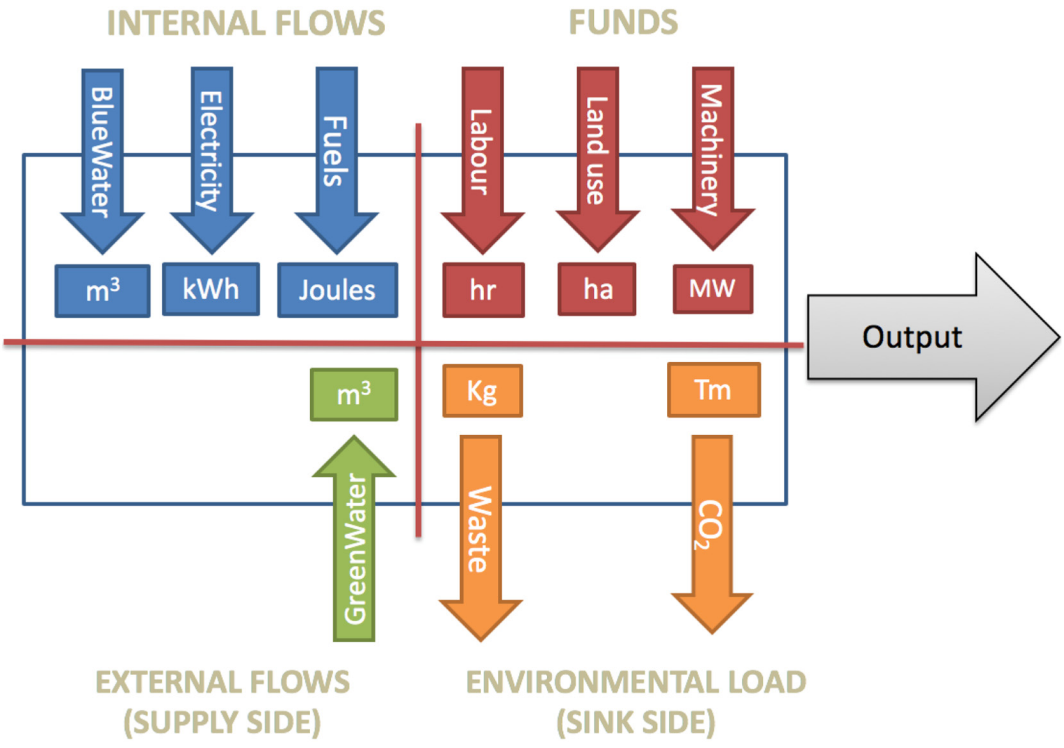

Fig. 2. Graphic representation of a processor.

(e.g., an individual wind turbine producing electricity), a wind farm made up of many wind turbines, a complex of alternative electricity production combined with a desalination plant used for irrigation, the agricultural sector, or an entire society. Clearly at each specific hierarchical level of analysis the definition of inputs and outputs in the processors and the corresponding accounting must be adjusted (semantically open approach).

Processors represent metabolic relations and are described using physical quantities (e.g. surface for land, volume for water, time for labor, power for machinery, electricity for energy). However, they can also be used to track economic costs and benefits by using the costs of the input flows and funds and the revenues of the useful outputs. By integrating the two types of information, a picture about both economic viability and biophysical viability and feasibility is obtained, which is useful to assess the operative and amortization costs, the net profits of the outputs, or the possible subsidies that are required for achieving economic viability.

Processors can be represented either as 'unitary' or 'sized' processor. In unitary processors, the values of the flows and funds exchanged are normalized per unit of output (e.g., the inputs and outputs per cubic meter of desalinated water produced, or inputs and outputs per ton of crop produced) or per unit of input fund element (e.g., the profile of inputs and outputs per hectare of land use for crop production). Hence, the unitary processors represent the 'technical coefficients' of the production process. They are useful for two main purposes: (i) to visualize and compare differences across different metabolic elements expressing the same function; and (ii) to scale up the effect of a change in size or technical characteristics of a specific processor in simulations of scenarios. Sized processors, on the other hand, refer to the actual size of the flows and funds observed in the system. Unitary processors can easily be converted into sized processors and vice-versa by, respectively, multiplying or dividing the profile of inputs and outputs by the size of the fund element used for the scaling.

Distinction between functional elements (a wind farm) and structural elements (wind turbines) is essential for scaling up the quantitative representation of metabolic performance. Processors describing specific structural elements (e.g., specific model of wind turbine) can be combined into a higher-level processor describing a functional element (e.g., a wind farm made up of a combination of different types of wind turbines). Therefore, representing the metabolic pattern with processors (relational analysis) allows the analyst to move across the hierarchical levels of the system. This is an important feature of MuSIASEM's relational analysis. In this way, it is possible to handle a simultaneous representation of the metabolic system across different levels of analysis (e.g., an individual wind turbine; a wind farm; the WEF system as a whole). The metabolic characteristics of the lower-level structural components weighted by their relative size define the metabolic characteristics of the upper-level functional element. This approach can be used in both diagnostic and anticipatory mode. The diagnostic mode explains the relations among metabolic characteristics observed across different levels, that is, how the characteristics observed at the upper level depend on those observed at the lower level. In the anticipatory mode, MuSIASEM is used to visualize expected changes in metabolic characteristics of the functional components at the upper level in response to changes in metabolic characteristics or relative size of lower-level elements (e.g., introduction of new models of wind turbines or an increase in the relative contribution of certain types of wind turbines in the wind farm).

The procedure for aggregating processors of lower-level metabolic elements into processors describing functional elements at a higher level is simple: inputs and outputs of the sized processors are summed respecting the common structure of the data array (blue water is summed to blue water, labor hours to labor hours, and so on). Moving up in this way in the hierarchical structure of the system, an overall assessment of the profile of inputs and outputs for the entire WEF system is formalized. At this level of analysis, the level of openness of the system (the level of self-sufficiency), the dependence on imports or subsidies, and the overall environmental pressure exerted can be checked. The procedure is illustrated for the selected case study in the Results section.

2.4. Data and material sources for the case study

Data used in this study were obtained from various sources. Primary data on the water and energy flows were provided by Soslaires Canarias S.L (personal communication) and cover technical coefficients of wind power plant, desalination plant, pumping, storing infrastructure, and irrigation related to the year 2015. Primary data on crop production were obtained from the agricultural cooperative and complemented with secondary data from statistics. Gross revenue and food prices are from the records of the official food wholesale market on the island where farmers sell their produce, using the most frequent food prices for the year 2015. Labor costs were calculated from the average salary of operation and maintenance workers and farmers in the area. The costs for irrigation and agrochemicals were estimated from the profile of required inputs. The cost of fertilizers was estimated using benchmark average values found for Spain. Data used for the processors are available in the Supplementary data files. Note that the analysis provided in this paper is but a starter for the process of co-production of knowledge claims. The quality of this preliminary characterization will be checked in the second phase of the project using participatory processes to build a validated representation useful for an informed process of deliberation.

3. Results

3.1. System description

The first step is to identify the functional elements required to stabilize the flows of water, energy and food metabolized by the WEF system and define the relations among these elements starting from the big picture of the whole system. This includes a definition of a boundary for the system in order to distinguish between exchanges of input and output flows that take place *inside* the WEF system and those taking place across the boundary with either the wider environmental context (the biosphere) or other socio-economic systems (e.g., the market or electricity grid in this case). A hierarchical set of relations over the different functional elements is then established up till the lowest level where it is still possible to identify structural elements.

As shown in Fig. 3, in this case, there are three functional components expressing three processes: (i) the production of electricity by the wind-farm (local wind electricity supply); (ii) the production of fresh water by the desalination plant (local desalted water supply); (iii) the production of crops on the local farm (local crop supply). Crop production uses: (i) electricity from both the local wind energy provider and the national grid, (ii) blue water from the local desalination plant and possibly from the nearby supply of reclaimed water (some farmers alternate these two water sources); (iii) green water in the form of privately-managed groundwater.

The electricity generated by the wind farm is used mainly, but not exclusively to power the desalination plant. As shown in Fig. 3, the electricity from the wind farm and the grid do not meet all the energy requirements of local crop production. For instance, the fuels consumed by the tractors operating on the farm have to be imported from outside the system (the socio-economic context). The desalted water is used exclusively for the local crop supply. However, some of the farmers who use the desalinated water also use a nearby supply of reclaimed water and/or groundwater to irrigate their crops. The ground water is managed by a private company. The crops produced by the farm are for the market and therefore go outside of the system.

The three functional elements in the WEF system (electricity supply, water supply, and crop supply) are each composed of a mix of different structural types (Fig. 4). The crop supply consists of eight different

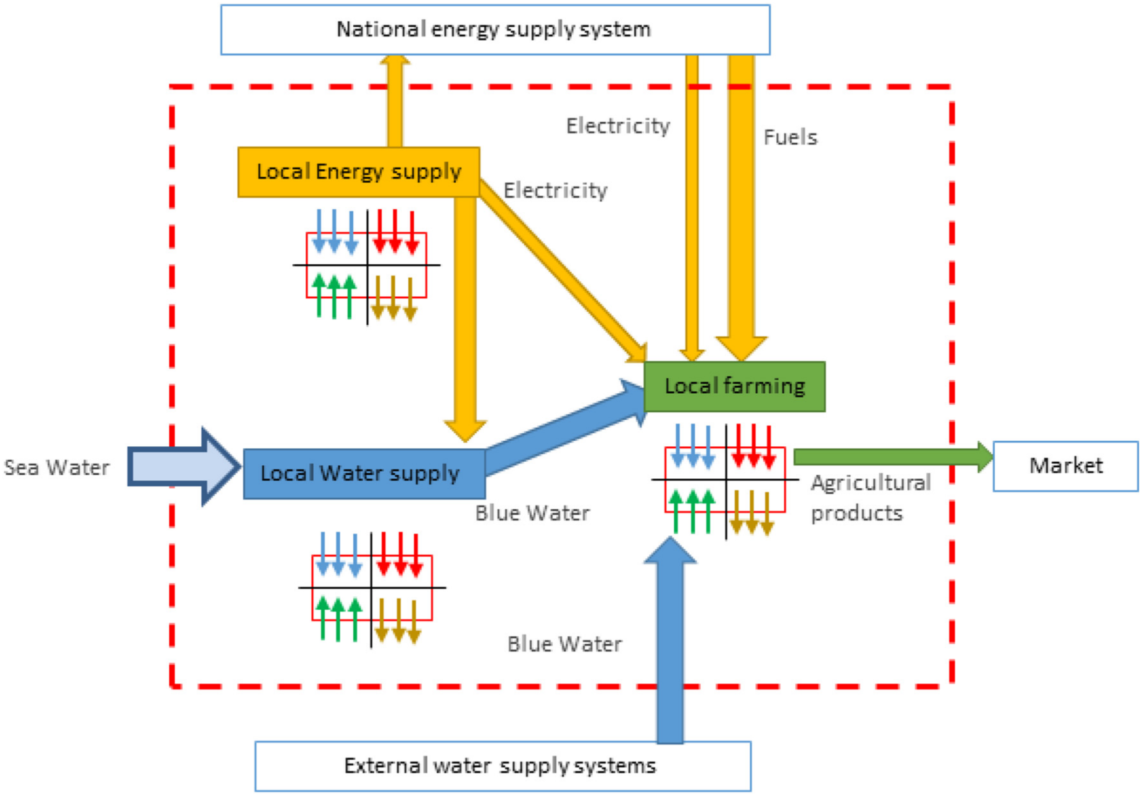

Fig. 3. Relational analysis of functional metabolic elements of the local WEF system in the island of Gran Canaria.

production systems (structural types: cantaloupe, watermelon, tomato, zucchini, beans, pumpkin, banana and moringa), the local electricity supply consists of four wind turbines, and the local desalted water supply consists of three structural elements: a desalination plant, a dammed pond used for storing the desalted water for irrigation (buffer), and the pumping devices, located outside the desalination plant, required for the water system supply. For each of these structural components a processor is created, as shown in Fig. 4.

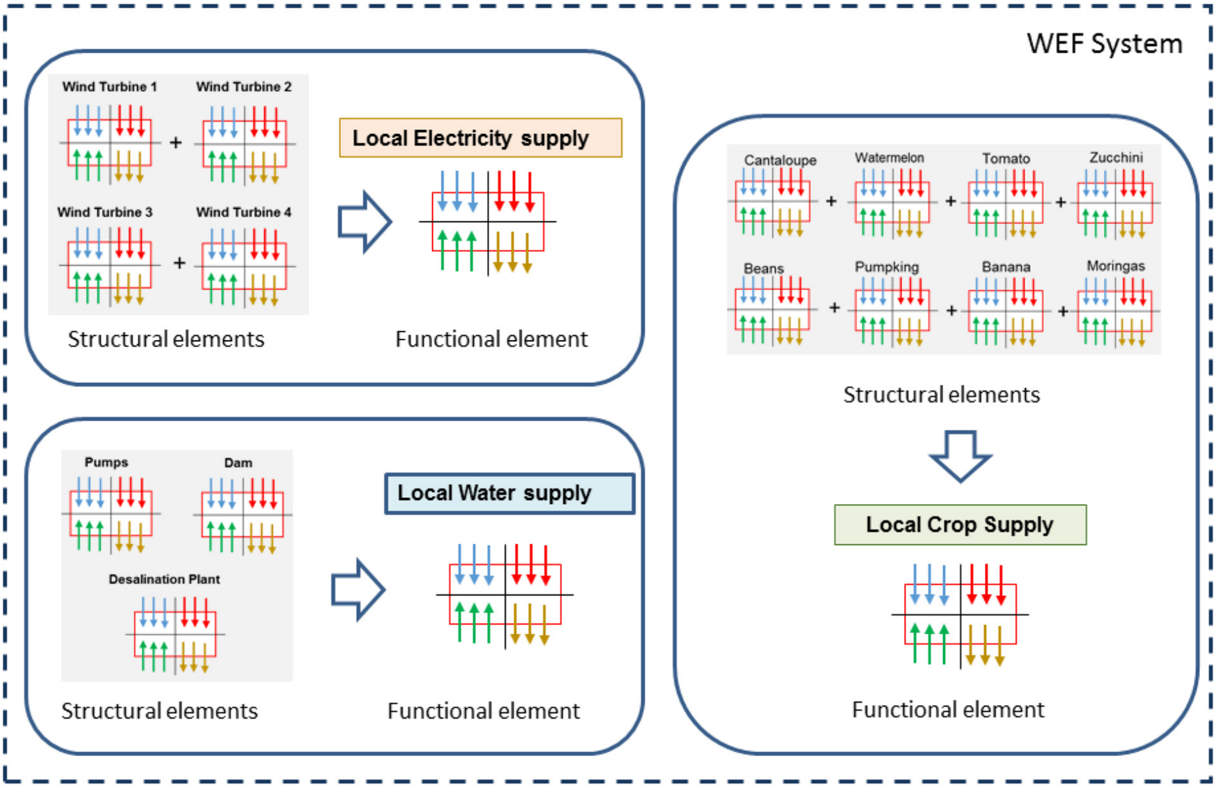

Fig. 4. Representation of the hierarchical relations between the processors of the three functional elements and their composing structural elements.

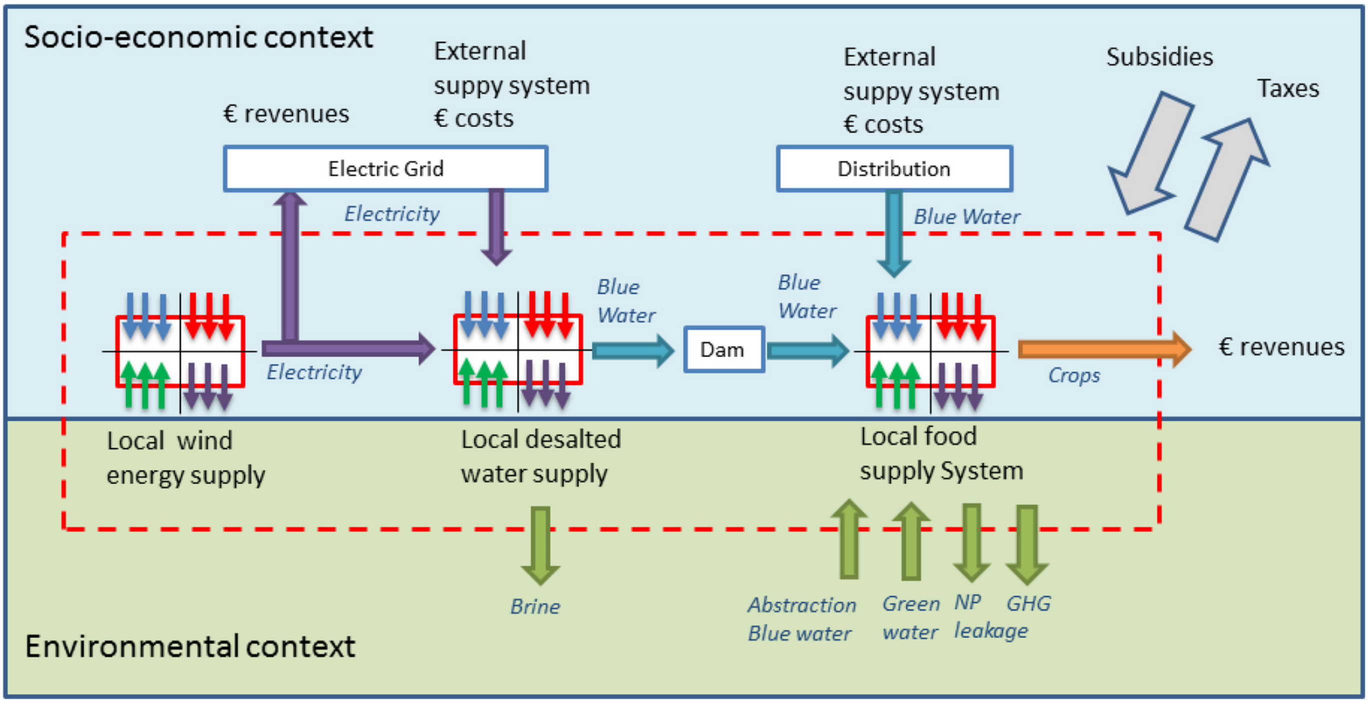

Fig. 5. Contextualizing the representation of functional elements in relation to the socio-economic context (top) and environmental context (bottom).

Establishing a bridge across the information carried by the processors of structural and functional elements at the different levels of analysis (Figs. 3 and 4), it is possible to understand the relation that the system has with both its socio-economic (economic reading) and environmental context (biophysical reading) as shown in Fig. 5. The economic reading is essential to check the economic viability of the system; the biophysical reading to check the environmental compatibility. As regards the latter, note that the arrows on the bottom of the scheme of Fig. 5 represent environmental *pressures* on the environment. They are not necessarily associated with environmental *impact*. For example, in this specific case, the production of brine as a by-product does not represent a big threat to the environment because, at the current scale of production, it is diluted into the sea. A similar assessment can be done for the other indicators of environmental pressure. A given level of abstraction of water from the local aquifer becomes dangerous and generates impact only when it exceeds the recharging capacity. Therefore, an analysis based on processors per se does not provide information about 'environmental impacts', but only about 'environmental pressures'.

3.2. Characterization of the processors of the various metabolic elements

Variables relevant for characterizing the performance (the profile of inputs and outputs) of the functional and structural elements in the form of processors have to be selected. This includes: (i) in the inputs: the required funds (land, human activity, power capacity), internal flows (electricity, blue water), and the external flows from the socioeconomic system (electricity, fuels, blue water) and the embedding natural ecosystems (green water, abstraction from the aquifer); (ii) in the outputs: the flow of useful products generated (electricity, desalted water, crops) and the waste flows released into the environment (brine, carbon dioxide emissions). The definition of the profile of inputs and outputs can be different for different types of processors. Desalted water is an output of the local water supply system (one of the functional elements) but is consumed inside the system and therefore no longer an output when considering the WEF system as a whole. Moreover, depending on the scope of the analysis, some of the inputs and outputs may be neglected if they result as irrelevant. Semantic decisions in this pre-analytical phase will determine the usefulness of the resulting quantitative characterization. For example, considering the requirement of water, is it important to distinguish between blue and green water? What are the relevant outflows that could represent a measurable impact on the environment?

Based on the biophysical reading of the processes taking place inside the system, a parallel economic reading can be generated by converting the flows of biophysical inputs into economic costs, and the flows of useful outputs into economic revenues. As noted earlier, processors can be represented as either unitary or sized processors.

3.2.1. Local wind energy supply

Fig. 6 illustrates the sized processor characterizing the wind farm complex. In this representation, funds and flows are expressed in absolute terms, reflecting the size of the local wind electricity supply system. This information is about how much electricity is produced on a year basis and the total amounts of inputs (flows and funds) necessary to guarantee this supply. The unitary processor (normalized to one unit of output, that is, 1 GWh/y) is available in the Supplementary data.

The information conveyed by the processor—including the power capacity (PC) installed—permits us to calculate the capacity factor (the maximum possible energy output of the device). Wind turbine power output depends on the strength and intermittency of the wind and hence is variable. The wind farm cannot provide maximum power capacity year round. Moreover, the desalination plant cannot use all the electricity produced by the wind farm at maximum power capacity. Hence part of the output of electricity of the wind farm is sold to the electricity grid of the island and part of the requirement of electricity of the desalination plants is obtained from the grid. Hence, the socio-economic context plays an essential role (as a 'virtual' functional element of external electricity supply) in providing electricity when it is needed but not produced by the local supply system.

Information on the monetary costs and revenues associated with this processor is also shown in Fig. 6 (in yellow). Part of the electricity produced by the wind farm is used for the desalination plant. However, as the local supply systems of wind electricity and water are both owned by the same company, no revenue is involved. Excess electricity outflow is sold to the electric grid at market price (with an investment

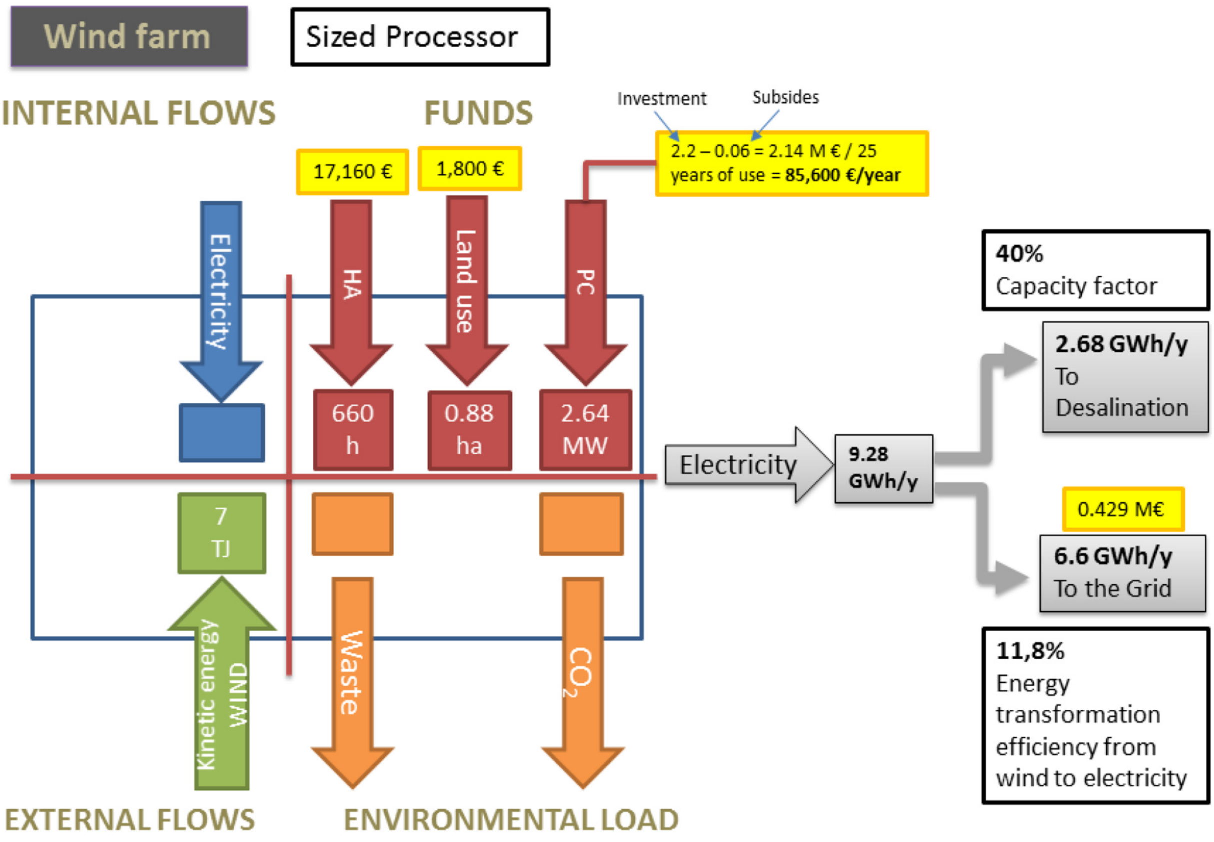

Fig. 6. Sized processor of the functional element local electricity supply (wind farm, aggregating data from the four structural elements), biophysical and economic (in yellow) reading.

bonus of 12€ per MW). The costs of the wind farm include operational costs (labor, and maintenance) and fixed costs of the installation of the infrastructure and technical devices. The fixed costs have been discounted over the expected life span of the infrastructure or devices. The external subsidies that Soslaires Canarias S.L. received at start up were also accounted for. In 1999, Spanish policy supporting renewable energies fostered premiums to promote private investments in wind energy. An amount of 526 Spanish Pesetas (3.16 EUR) per kWh was paid to facilities with power lower or equal to 50 MW for several years (IDAE, 1999). Additionally, the Spanish national entity responsible for renewable energy policies (IDAE - Institute of Diversification and Energy Saving) provided financial support to ensure proper execution from 2002 until 2010. However, since 2010, the only subsidies the WEF system has received have been agricultural subsidies.

The carbon dioxide emission involved in the operation of this wind farm has been estimated based on an average of 6 g of carbon dioxide emitted per kWh (EWEA, 2018).

3.2.2. Local desalted water supply

The sized processor for the functional element local desalted water supply (integrating the characteristics of its three lower-level elements) is shown in Fig. 7. The unitary processor is not shown but available in the Supplementary data. The desalination plant uses electricity from the grid when the wind farm does not meet its demand. Brine outflow represents a potential impact on the environment, but in this particular desalination plant, so close to the sea, it may be assumed insignificant as the brine is not poured directly into the sea but through a filtered well.

The economic data (Fig. 7, in yellow) provides relevant additional information, such as: (i) the cost of the electricity purchased from the grid; (ii) the cost of the labor required for the operation of the plant; (iii) the cost of external services for the maintenance of the machinery; (iv) the annual cost of renting the land where the desalination plant and pond are located; (v) the annual amortization costs of the fix investments (estimated); and (f) the revenues of selling the desalted water to the local agricultural cooperative. The price of the desalted water is higher (ranging from 0.6 to 0.83 €/m^3 in the period 2010–2016) than that of groundwater (between 0.5 and 0.6 €/m^3) and of (subsidized) reclaimed water (between 0.45 and 0.53€/m^3), but there is not sufficient underground water for agricultural irrigation in the area.

3.2.3. Local food supply

The flows and funds related to the agricultural production of the cooperative (functional element 'local crop supply') are shown in Fig. 8. This sized processor represents the aggregated output of the eight crops cultivated. Water inflows to the cooperative are divided into the desalted water from Soslaires Canarias S.L. and underground water. Groundwater can be obtained either directly from the biosphere (through wells operated by the farmers) or from the techno-sphere (from the grid against payment by the farmer). In this case, the input from the biosphere is accounted for in the 'virtual processor' associated with the system of abstraction and distribution of water to the farmers operating outside the boundary of the analysis.

Depending on the purpose of the analysis, selected information provided by this multi-scale system of accounting can be further elaborated. For example, when looking for indicators of environmental pressure, the following information would be relevant: (i) the biophysical information conveyed by the processors describing the structural elements inside the system boundaries, such as the flow of nutrients and pesticides, the extraction of underground water; and (ii) the dependency of the system on imported flows (externalization of the environmental pressure to the producers of the imported flows). As noted earlier, information about environmental pressure has to be georeferenced to assess environmental impact. On the other hand, if the information generated is to be relevant for economic agents, the

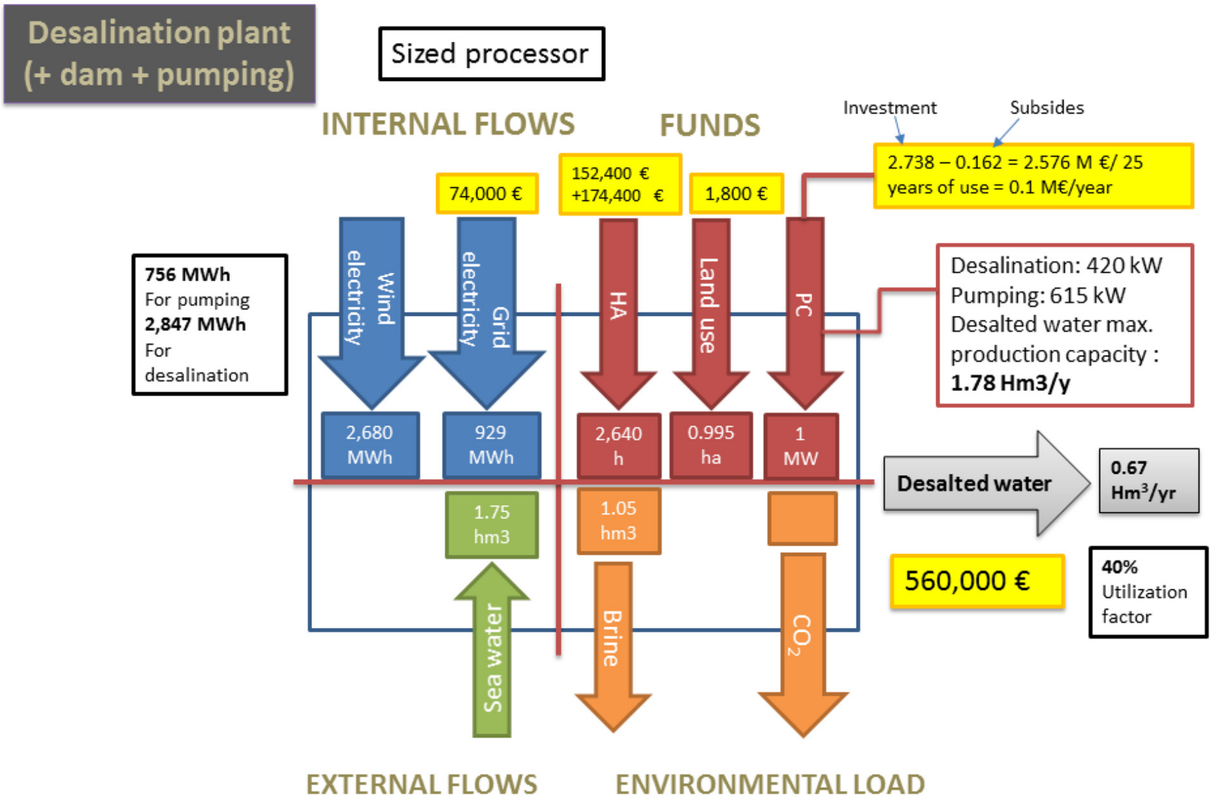

Fig. 7. Sized processor of the functional element local desalted water supply (aggregating data from the three lower-level structural elements); biophysical and economic (in yellow) reading.

functional elements associated with the activities of the relevant economic agents have to be identified first.

Regarding agricultural subsidies, farmers who cultivate certain vegetables, fruits, ornamental or medicinal plants can receive subsidies under the "Community Support Program to the Agrarian Productions of the Canary Islands" (POSEI, 2015). The extent of the economic support depends on whether or not the farmers are consolidated in agricultural cooperatives, the type of crop cultivated, and whether or not crops are destined for marketing outside of the Archipelago. For example, the production of banana and tomato receives greater support, especially if marketed outside of the Archipelago. Thus, in principle, it is possible to know the amount of agricultural subsidies received by the farmers who applied for it for each of the crop systems studied. However, this information was not disclosed in this case study.

3.2.4. Processor of structural elements

Moving down in the hierarchy of levels of analysis, we arrive at the characterization of the individual structural elements that make up the functional elements. For example, looking 'inside' the functional element local crop supply, we find the processors describing the operations of the eight individual crop systems (as described earlier in Fig. 4). Processors characterizing individual structural elements are not shown here but illustrated (for the eight crop systems) in the Supplementary data.

3.3. Aggregation of processors across the various functional elements

As indicated earlier in Section 2.3, the procedure for aggregating the information carried by the processors is flexible and depends on the purpose of the analysis. The pre-analytical decision about the choice and definition of functional and structural metabolic elements is essential in this process. Especially when adopting an economic narrative, the definition of functional units operating inside the system depends entirely on the choices made by the analyst. In this particular case, for example, there are two economic agents operating in the system: (1) the private company Soslaires, uniting the two functional elements local electricity supply and local water supply into one single economic agent; and (2) the farming cooperative, corresponding to a single functional unit made up of eight different structural elements (the crop production systems). As shown in Fig. 9, MuSIASEM not only provides useful information on the biophysical performance of this WEF system, but also on the performance of the local economic agents through the assessments of monetary flows.

The economic narrative can also be applied to the big picture of the entire WEF system by moving up another level in the hierarchy. At this level, the economic interaction of the local system (composed of different local economic agents) with its wider socio-economic context can be studied. For example, the role of the various monetary flows (e.g., subsidies and taxes) in stabilizing the metabolic pattern can be quantified and evaluated. In fact, the WEF system can be perceived as a functional unit that supplies society not only with crops and the surplus of electricity but also with other socio-economic services, such as employment and hence the reproduction and livelihood of the local community. Thus, MuSIASEM provides two different visualizations of the economic reading: (i) one providing information relevant for the specific economic agents operating inside the system; and (ii) one providing information relevant for the discussion of policies at the community or regional level.

4. Discussion

Given the illustrative nature of this study, approximate data have been used and some of the inputs and outputs of the various processors have been estimated for lack of data. A more robust assessment will be obtained through participatory processes with local farmers in the second phase of the project. Nevertheless, this preliminary analysis shows that MuSIASEM is a powerful approach to study the sustainability of integrated WEF systems. It can answer questions such as: How much net

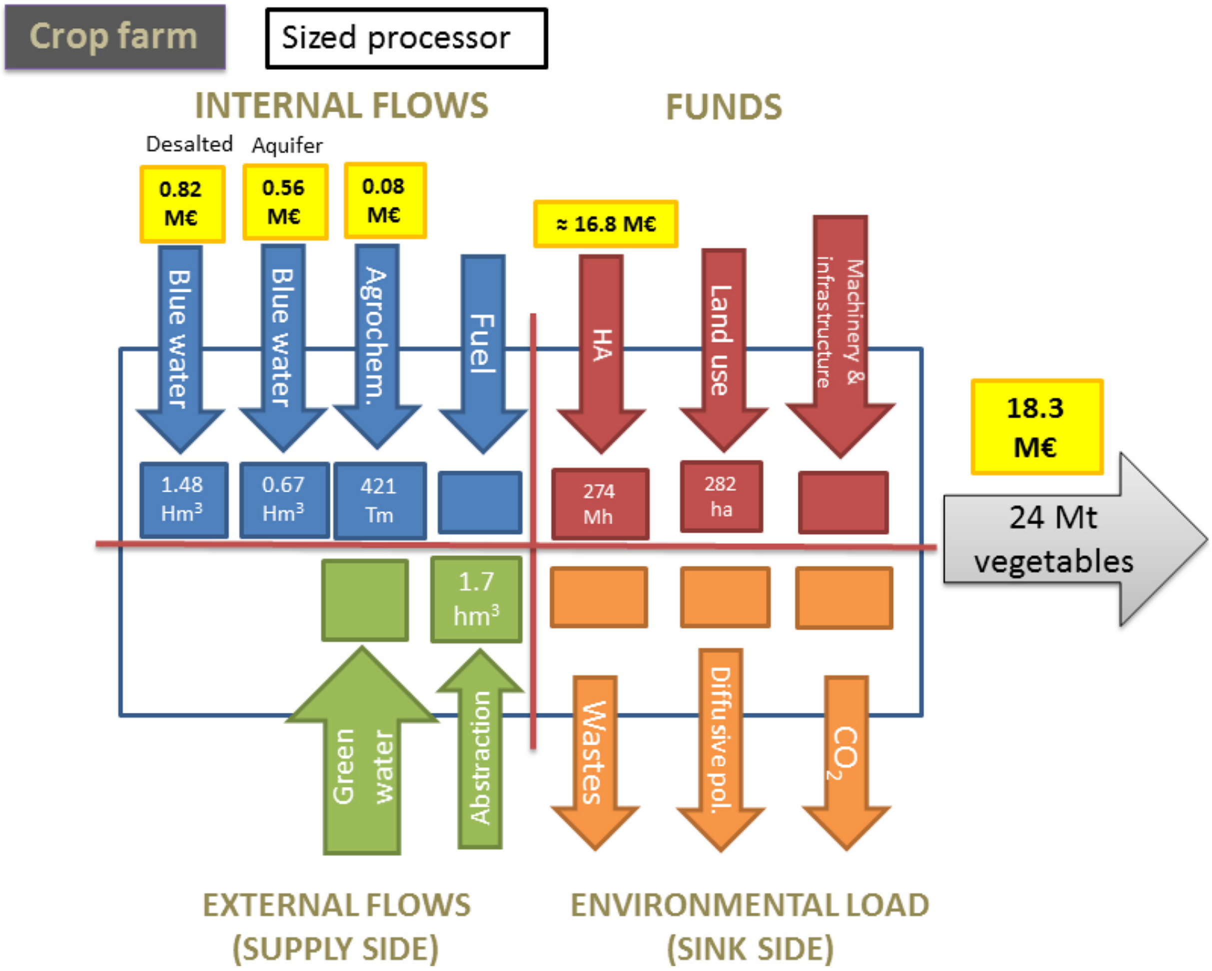

Fig. 8. Sized processor of the functional element local crop production; biophysical reading complemented with economic data (in yellow).

energy, water and food are being produced? Is this WEF system self-sufficient? What are the possible external and internal constraints? What is the economic viability of the system? Is it feasible to extrapolate this system to other areas?

The wind turbines provide part of the energy used by the desalination plant and the desalination plant provides part of the water used by the farms. In the same way, the farms provide part of the food used by the population in the island. An informed discussion of the performance of this system requires an identification and analysis of the relative importance of the various functional elements and the significant constraints affecting the performance of the system. In relation to this point, the interaction with the context is essential to assess the desirability, viability and feasibility of this solution. For example, wind turbines produce electricity that cannot always be used by the desalination plant (water demand is not linked with wind availability). So, the unused electricity has to be sold to the grid. The local supply system needs to be backed-up by an external supply/demand system. Also, the desalination plant requires electricity that cannot always be produced by the wind turbines, so a grid must be available to guarantee the continuity of operations. Additionally, if agriculture needs more water than the desalination plant can supply, the option of extra supply of water must be available. Again, the local supply system needs to be backed-up by an external supply system. Finally, the people of Gran Canaria require a larger quantity and variety of products compared to the few vegetables and fruits produced in this system. The local crop supply system must be integrated in a larger food supply system. These observations might seem obvious, but the adoption of this analytical approach helps analysts to contextualize its results in relation to the specificity of the considered situation in order to avoid endorsing misleading narratives. When dealing with sustainability issues, there are pros and cons for each technical solution and these must always be contextualized in relation to the biophysical limits determining the option space. The local case study presented here is relatively simple and manageable, but the same principles and outputs apply to larger and more complicated WEF systems.

The WEF system studied is not self-sufficient. It relies on other external systems for its supply of energy carriers (fuels and electricity) and water for its operation. Naturally, this does not imply that alternative energy generation and desalination are useless or bad. On the contrary, they help improve the sustainability of economic activities. The point made here is that in order to get the most out of proposed alternative solutions, it is essential to develop an analytical framework capable of: (i) providing a clear vision of the degree of *openness* of the WEF system; (ii) understanding its possible limitations; and (iii) characterizing the pros and cons across different levels and dimensions.

It is important to keep in mind that in this area it is possible to use different kinds of water (groundwater, desalted water, reclaimed water) but that these are not necessarily apt in quality (salinity and agronomic requirements) and quantity to the different crops cultivated. Moreover, the use of underground water relies on a private market and management and hence is subject to availability and price variations beyond control. So, for the farmers, the desalted, more expensive water is a warranty of supply under stable conditions (price and management). The possible subsidies received by the wind farm and

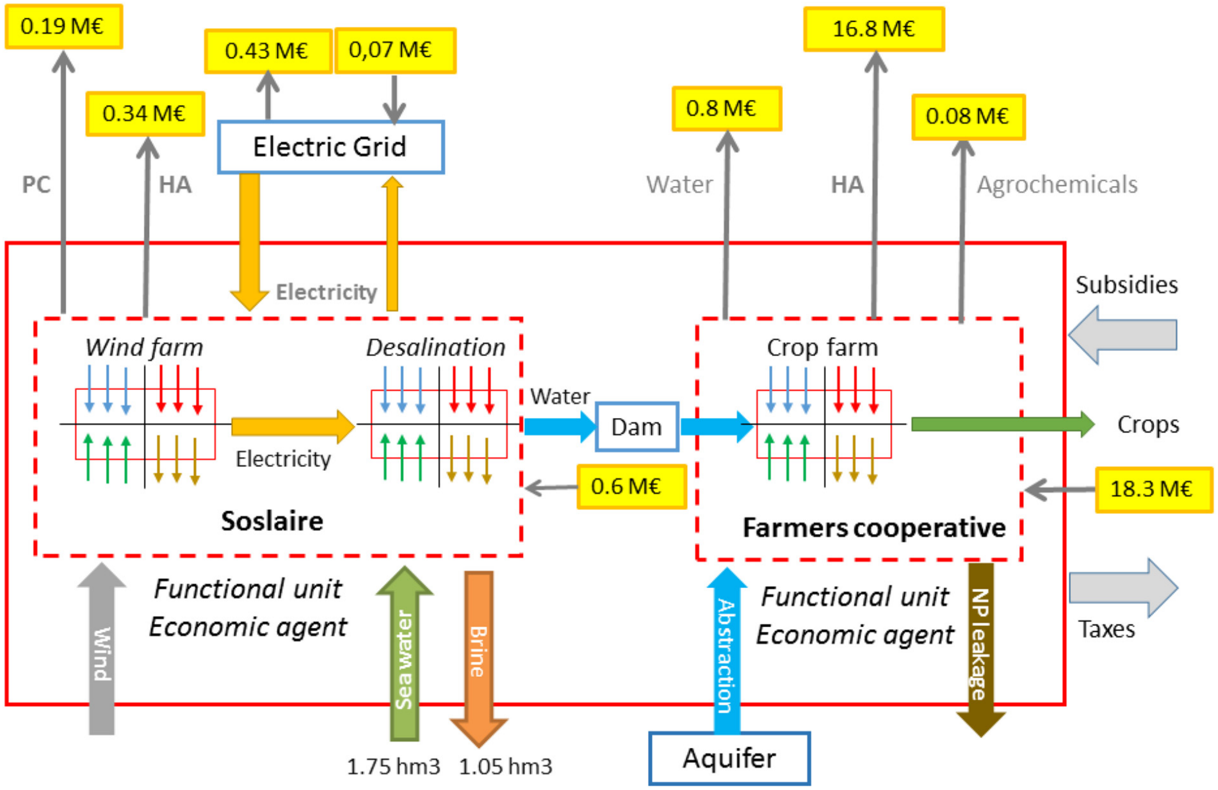

Fig. 9. Economic representation of the WEF system relevant for local economic agents.

desalination plant should guarantee their economic viability. The farmers can assume the high cost of desalted water considering (i) the existence of agricultural subsidies, and (ii) the local market price policy. It is important to be aware of these location-specific arguments when considering similar solutions for other areas.

Gran Canaria depends on desalted water in spite of its cost, because desalination is one of the very few viable water sources. However, the supply of desalted water is normally prioritized for urban consumption. Water requirements of the agricultural sector are high, and the economic return of agricultural water use is much lower compared to other socioeconomic sectors. This means that agricultural activity requires a large quantity of water resources to produce comparatively little value added. For this reason, agriculture flourishes only where water resources are not limited or where the water used in agriculture does not represent an opportunity cost to the development of other sectors.

On the other hand, the heavy dependency on external food sources does severely affect the food security and food sovereignty of this territory. This is why the Canary Islands try to control as much as possible their internal food production. However, a close look at this particular local WEF system shows that the mix of crops produced does not supply the basic elements of the local diet (based mainly on cereals, tubers, grains, oils, and animal products), but focuses on fresh crops with high costs to import due to their relatively high water content and perishable nature. Hence, the food production of this local WEF system contributes only marginally to the food security of the archipelago.

This discussion seeks to emphasize the variety of issues and concerns involved in a comprehensive assessment of the performance of a local WEF system in relation to its socio-economic and environmental context. Given the complexity of the picture, relevant information should be gathered in the form of participatory research involving the local actors. Co-production of information with social actors is needed to guarantee not only the quality of the quantitative assessment (the data entered in the accounting protocol) but also the quality of the pre-analytical choices made at the moment of representing the relations over the various functional elements (i.e., what should be considered *relevant* information?).

5. Conclusion

Water-Energy-Food (WEF) nexus security becomes extremely important in isolated areas and islands when one or more of the natural resources are scarce. However, the entanglement between water, energy and food flows associated with the nexus entails a formidable epistemological challenge for conventional reductionist science (Giampietro, 2018). This challenge calls for new approaches to the quantitative analysis of the nexus.

In this paper, a local case study in the Canary Islands—a private desalination plant that uses wind electricity to provide water for an agricultural cooperative located in the southeast of the island of Gran Canaria—was used to illustrate the potential of MuSIASEM in providing an integrated assessment of the WEF nexus in relation to sustainability.

The illustration of the MUSIASEM approach has shown that it is possible to generate a robust quantitative assessment of the energy, water and food nexus using insights from complexity theory, by establishing relations over processors conveying information referring to different dimensions and scales of analysis. This allows a holistic reading of the big picture as well as of the functioning of the various constituent components of the system, each of which provides relevant information about the WEF system performance. In this way it becomes possible to explain the characteristics observed at the large scale from the characteristics of the functional elements operating at lower levels and to identify limiting factors.

The flexible information space created by MuSIASEM can be used either (i) in a ‘diagnostic mode’ to explain the observed metabolic performance of the functional elements and to compare it with similar functional elements across levels or in other systems, or (ii) in ‘anticipatory mode’ to anticipate the effects of possible changes in the characteristics of the processors or in the combinations of lower-level structural elements on the functioning of the system as a whole. The anticipatory mode implies the aggregation of representations referring to different hierarchical levels of analysis; the way this is done entirely depends on the interest of the analyst.

A second round of analysis, carried out in co-production with local social actors, is under way to check: (i) the quality of the data; (ii) the quality of the representation of the relations over different processes; (iii) the plausibility of the assumptions used in the framing of the sustainability predicament. Although the preliminary analysis presented in this paper cannot be used as such to inform policy, it is key in enabling and facilitating the participatory process, and therefore a valuable result toward a different type of science in which sustainability assessments are carried out in the field together with the social actors and not from behind the desks of university offices.

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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.2019.06.422.

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