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Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making

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The paper introduces a framework and set of methodologies that define the linkages between the interconnected resources of water, energy and food, and enable explicit corresponding quantifications. The paper presents a new water–energy–food (WEF) Nexus modelling tool (WEF Nexus Tool 2.0) based on that framework which offers a common platform for scientists and policy-makers to evaluate scenarios and identify sustainable national resource allocation strategies. The tool is applied to a case study focusing on Qatar, a hyper-arid Gulf country.

Keywords: modelling tool; integrated policy; sustainability index; water and food security; nexus; Qatar

Introduction

The unprecedented increase in global population, the growth of middle-class societies and their increased purchasing power, climate change, economic development, international trade, health and environmental concerns, all play roles in magnifying or reducing the growing stresses on the vital resources of water, energy and food (WEF). The absence of systemic management strategies threatens the ability of these resources to meet growing demand. Projections for water availability and quality, food and energy availability, soil and air quality, among others, are alarming. These alarms point to one major conclusion: 'business as usual' is no longer viable. Indeed, they call for a fundamental shift in the manner in which we understand and manage resources: a shift away from traditional 'silo' approaches toward more integrative, systems approaches. While such a shift is promoted on multiple global stages, progress remains fragmented and tends to focus on specific, singular aspects of the nexus.

The WEF systems are highly interconnected: food production requires both water and energy; pumping, treating, and transporting water requires energy; energy production requires water (Mohtar & Daher, 2012). The three systems are also affected by forces that can exacerbate or help mitigate the stresses between them. National strategies for governing the management of one system are often developed independently of the other two systems, thus failing to consider the interconnections between the three. This often results in conflicting strategies and increased competition for the same resources. While 'nexus' discussions have gained thrust in policy and science arenas over the past few years, there remains a need for increased awareness and integrative planning amongst the involved entities. This need can be addressed through

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a quantitative framework using tools that will guide increased cooperation and integrated planning. This paper reviews the existing tools and then presents a new, scenario-based framework and tool: the WEF Nexus Tool, and in the context of its application to a case study country (Qatar).

Literature review

Background

A 'nexus' among water, energy and food was identified during the 2008 World Economic Forum annual meeting (World Economic Forum, 2011a); and the WEF nexus was identified as a Global Risk in 2011 (World Economic Forum, 2011b). The Bonn Conference (2011) 'Initiating Integrated Solutions for the Green Economy' marked a milestone, recommending that water, energy and food securities be considered in an integrative manner. The conference focused on ensuring that the interdependency between water, energy and food security is "explicitly identified in decision-making". Three years later, during the 'Sustainability in the Water–Energy–Food Nexus' conference (GWSP, 2014), a call for action was issued by policy and research communities worldwide to develop strategies that address a comprehensive nexus approach. The sustainable development goals (SDGs) also call for an integrated nexus approach (Weitz, Nilsson, & Davis, 2014). Finally, UN Secretary General Ban Ki-moon highlighted the use of a nexus approach, and urged the inclusion of environmental, social and economic dimensions (GIZ, 2012).

Current stresses facing our global community, together with other, interrelated, projected challenges, are the main drivers behind the WEF nexus discussion. At the current rate of population growth, the agricultural sector is challenged with doubling food production by 2050 (OECD-IEA, 2010). About 71% of current world water withdrawals are attributed to the agricultural sector (McKinsey & Co., 2009). By 2050, an anticipated 55% increase in global water demand will be needed to address increased manufacturing, electricity generation and domestic use: it is projected that more than 40% of the global population will live under severe water stress (UNESCO, 2014). Finally, in 2010, the energy sector consumed an estimated 15% of the global water withdrawals (IEA, 2012), and contributed two-thirds of global greenhouse gases (IEA, 2013). Securing alternative sources of water through desalination, pumping and treatment carries high energy costs. In the Middle East and North Africa region, where 38% of global desalination takes place, electricity demand attributed to desalination tripled between 2007 and 2013 (IRENA, 2013). Between 2003 and 2007, two-thirds of the increase in global maize produced was used for biofuel production (World Bank, 2009), setting off the global food price hike of 2008, which was largely attributed to biofuel subsidies (Commonwealth, 2009).

Gap identification and tools review

Securing water, energy and food supplies for current and future generations, while maintaining a healthy environment and successful, sustainable economies, is a complex challenge. Major power and responsibility lie in the hands of policy-makers governing the different pieces of the puzzle. The scientific sphere has made progress in understanding and quantifying the challenges that lie ahead, but questions remain regarding how the knowledge can best be transferred to enable informed decisions in the policy/decision-making sphere.

Decision-makers currently lack effective tools that allow accounting for different resource allocation strategies and an understanding of the trade-offs between the different systems. Tools exist that address specific aspects of the nexus. These include WEAP (SEI, 2014), LEAP (SEI, 2013), MuSIASEM (FAO, 2013), and CLEWS (KTH, 2013), among others. WEAP (Water Evaluation and Planning) uses an integrated approach to water resource planning. LEAP (Long-range Energy Alternatives Planning System) is directed at energy policy analysis and climate change mitigation assessment. MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism) offers a method to characterize flows of different systems within society. CLEWS (Climate, Land, Energy and Water Strategies) further develops an integrated systems approach to determine the interactions between interconnected sectors. A more comprehensive list of tools can be found in FAO (2014) and IRENA (2015).

Each tool offers important advances over analysing separate resource systems, as well as different methods for looking at distinct flows between the separate systems (Table 1). Nevertheless, decision-makers still do not have access to comprehensive tools that:

- are inclusive and multi-scale;
- define and quantify interconnectivity between water, energy and food; and
- support development of an integrative strategy for holistic management and planning for the future of these resources.

Thus, the need remains for a generic, holistic framework that considers the existing interlinkages between the systems and offers decision/policy-makers a solid foundation for debate, discussion and action.

Study objectives

The main objective of this paper is to introduce the WEF nexus as a platform for resolving current and foreseen bottlenecks. The platform is governed by a comprehensive framework that reflects the multidimensional, interdisciplinary nature of resource management projects. Specifically, the objectives of the paper are:

- To present a scenario-based, integrated framework, and an application tool based on that framework, that offers an explicit quantification to the existent interlinkages between nexus components and affecting externalities.
- To evaluate the tool's performance through assessment of its functionality and output, and to perform sensitivity analyses on its parameters.
- To demonstrate the tool's utility as a decision-making guide in a case study for Qatar's food security.

In the following section, a scenario-based framework is presented, and governing methodologies for quantification are discussed.

Methodology

Conceptual scenario-based framework

Figure 1 shows a generic conceptual representation of the interconnections between the water, energy and food systems. The framework starts by identifying nationally consumed food products. A portion of these products are domestically produced and consumed (DPC), while others are imported (IMP). Products could also be domestically produced and exported (DPE).

Table 1. Review of Nexus Tools (IRENA (2015).

	Inputs		Outputs	
Tool and reference	1. (a) Main inputs	2. (a) Energy	2. (b) Water	2. (c) Food
Climate, Land-use, Energy and Water (CLEW)	• Extensive data requirements • Technical and economic parameters of power plants, farming machinery, water supply chain, desalination terminals, irrigation technologies, fertilizer production, etc.	• Energy balance, including power generation and refining • Energy for food • Foreign (virtual) energy	• Water balance • Water supply and desalination • Water pumping • Water for food • Water for energy (hydropower, power plant cooling, biofuel crops)	Irrigation technologies: • Use of fertilisers • Use of farming machinery
WEAP-LEAP (SEI, 2013)	• Extensive data requirement • Techno-economic details of energy technologies	• Detailed analysis of energy demand, transformations and stocks • Energy balances	Watershed hydrology and water planning: • Physical and geographical simulation water demands and supplies • Groundwater, water quality and conservation, reservoirs and hydropower	
FAO's nexus assessment methodology (FAO, 2013)	• Indicators that are already available • Key classifications of the country under study to place it under country typologies	• Specific to each type of intervention, but a large choice (e.g., energy consumption and production)	• Specific to each type of intervention, but a large choice (e.g., water pumped, water for energy, etc.)	• Specific to each type of intervention, but a large choice (e.g., yields, harvested food, etc.)
MuSIASEM The Flow-Fund Model (FAO, 2013)	• Extensive data requirement • Socio-economic indicators, including workforce evolution • Availability of land • Climate change impacts • Characterization of all flows	• Energy flows in society (of fossil fuels and electricity)	• Water flows in society (e.g., for drinking, domestic use, irrigation, industrial processes, etc.)	• Food flows in society

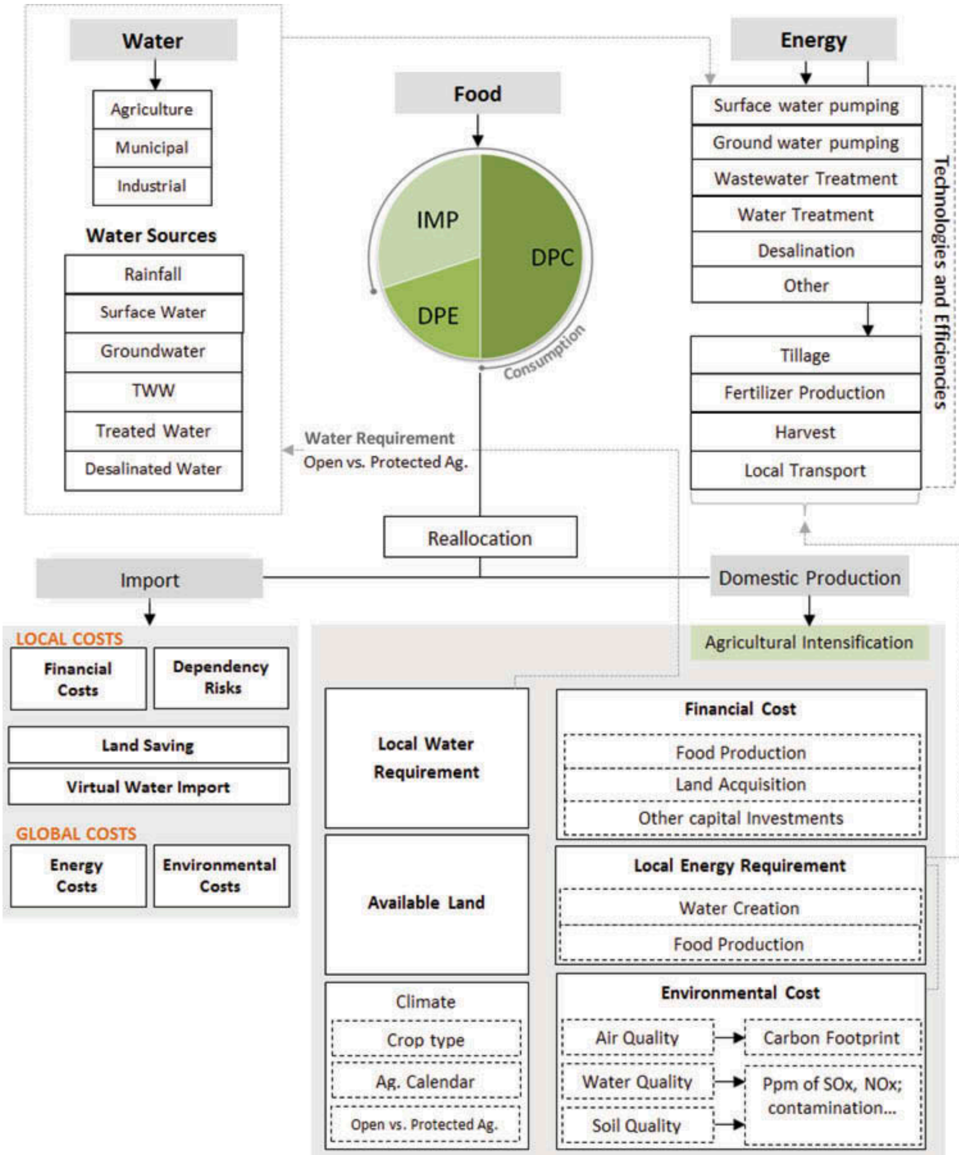

Figure 1. Water, energy and food conceptual scenario-based framework. DPC, domestically Produced and Consumed; DPE, domestically produced and exported; IMP, imported; TWW, treated wastewater.

Each component is associated with different costs and risks, and is generally driven by policy choices, toward either a greater reliance on local production or on imports. Based on an identified food profile, and national water and energy portfolios, the local feasibility of any proposed scenario can be assessed while respecting the systems' interconnections.

Importing food products carries additional financial requirements associated with transport costs. Transporting products by land, air or sea requires energy and carbon is emitted. Countries relying heavily on food imports face risks mainly characterized by the inability of current exporting sources to maintain supply, and increasing vulnerability to global food price fluctuations. Risk in this context carries a political dimension (security aspect), as well as a health threat element (possibility of contaminants in imported food products). Through import a country may save on local land and water resources. Alternatively, aiming to reduce dependence on imports in favour of increased reliance on local food production requires a profound understanding of the potential of the nation's local resources as well as the readiness of the country to withstand requirements accompanying such a shift in securing food needs.

Considerations for local agricultural expansion should include the following:

Water

- Quantify water requirements for alternative food self-sufficiency scenarios as these are controlled by the type of agriculture and technology.
- Study and quantify available conventional and non-conventional water sources currently allocated for agricultural practices.

Land

- Quantify land requirements for alternative self-sufficiency scenarios.
- Allocate and quantify areas of land suitable for growing proposed products.

Financial

- Quantify the cost of local production, including capital costs, production and operational costs.

Energy

- Quantify energy needs, which are divided between securing water (through pumping, treatment or other) and the energy required for agricultural processes (tillage, harvest, fertilizer production and local transport). Energy requirements are determined by the technologies used and their respective efficiencies.

Environment

- Quantify the environmental impact on air, water and soil. This paper will focus on the carbon footprint resulting from energy use; the amount of emitted carbon depends on the type of energy and technology used.
- The local climate determines the type of products that can be grown, as well as the time of year and type of agriculture optimal for their growth.

Quantifying flows between water, energy and food systems

The proposed conceptual framework serves as a foundation for defining the relations that exist between the three systems. Explicit quantification of these relations is imperative for proper assessment of different scenario variations and guides the decision-making process. Figure 2 demonstrates the flows that exist between water, energy and food based on the presented conceptual framework.

By proposing a food self-sufficiency scenario, food products are quantified in tons (ton) of DPC, DPE or IMP. While IMP are secured through trade with global markets, DPC and DPE consume local resources. Depending on the type of food product and their respective local yields (ha/ton), their land requirement is defined (ha). Financial requirements for growing the food products (US$/ton), as well as profits, depend on the type of

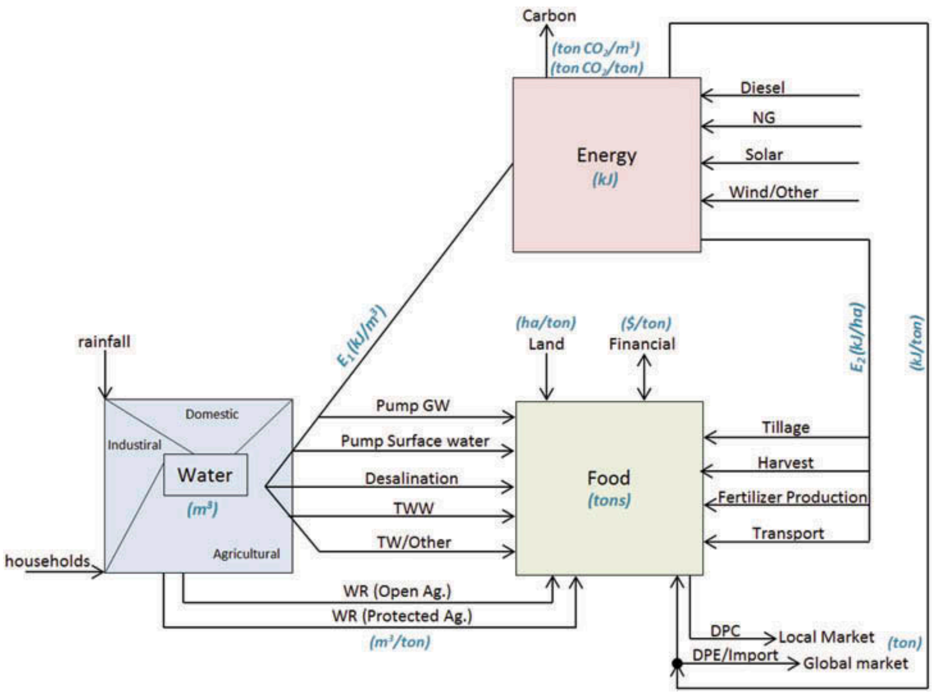

Figure 2. Block diagram demonstrating the water–energy–food nexus framework.

product produced. This cost is based on market prices, which do not reflect subsidies that might be put in place to support local production.

The amount of water needed (m^3) for a proposed self-sufficiency scenario depends on the water requirements (WR) (m^3/ton) of the type of food product grown locally. It is primarily affected by the type of agriculture and technology used (open field agriculture versus green house versus other). The water needed for growing food products in open fields versus greenhouses may vary widely. WR is also highly affected by the selected irrigation method. Different sources and amounts of water are allocated for agricultural production. There is an energy cost E_1 (kJ/m^3) to securing water, whether through pumping (ground or surface water), desalination, treating wastewater or other.

In addition to the energy cost of securing water, energy is also required for food production processes, including tillage, harvest, fertilizer production and local transport – E_2 (kJ/ha). Energy is secured through various available sources and, depending on the need and source, the carbon footprint is quantified C_1 (ton CO_2/kJ/m^3) and C_2 (ton CO_2/kJ/ha). From a global perspective, energy is required to transport imported food products – E_{IMP} (kJ/ton), and respective carbon is emitted C_{IMP} (ton CO_2/ton).

Tool structure (WEF Nexus Tool 2.0)[1]

Having defined the interconnections between the three systems, this section will introduce the WEF Nexus Tool structure (Figure 3) which allows for the creation and assessment of different scenarios and consists of inputs that reflect national food, water and energy strategic options. The scenario is created by the user by choosing the following:

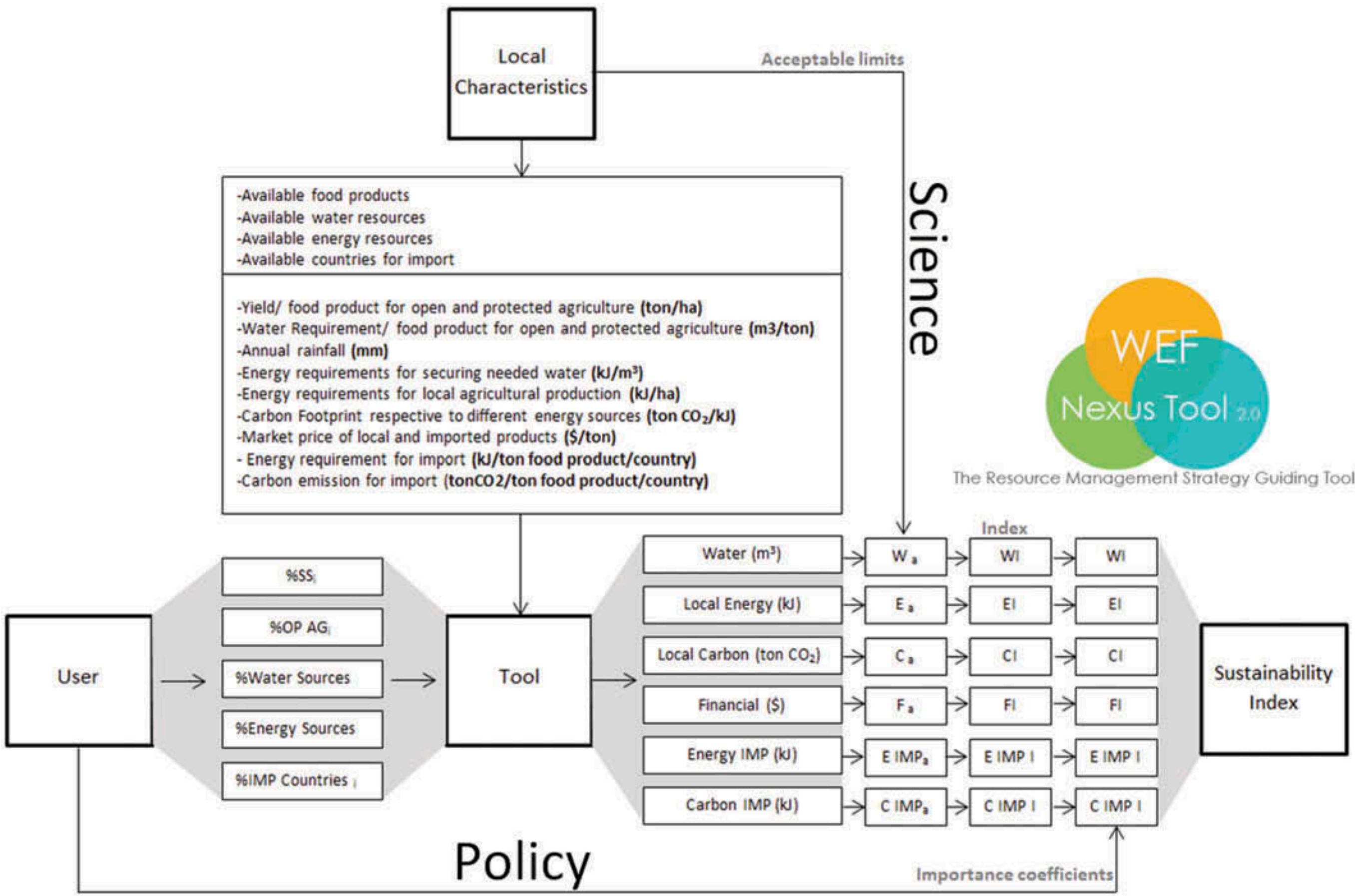

Figure 3. Tool structure and the calculating sustainability index.

- Percentage of self-sufficiency of food products (%SS) in a selected national food basket (e.g. %SS of tomato 50%, %SS of cucumber 20%). 'Self-sufficiency' is used as a representation of the ratio of a specific food product produced locally to the total national consumption of the same food product.
- Percentage of food products grown in open agriculture conditions (%OpAg) (versus protected agriculture, greenhouses) for each (e.g. 30% of tomatoes produced in open conditions, while 70% of are produced in greenhouses).
- Percentages for each of the different water sources for the given scenario (e.g. 30% desalination, 70% groundwater).
- Percentages of energy sources for the scenario (e.g. 30% fuel oil, 20% wind, 50% solar).
- Percentage supplied and sources of countries for the imported food products (e.g. 30% of imported tomatoes from Jordan, 70% from Lebanon).

Using the five scenario inputs above, and based on the local characteristics of the area under study (Figure 3), the tool assesses the given scenario by calculating the following:

- Total water requirement for the scenario W (m^3).
- Total land requirement L (ha), based on local production and yields.
- Local energy requirement E (kJ), split between energy needed for securing the required water (E_1) and energy for local food production (E_2).
- Local carbon footprint $C = (C_1 + C_2)$ (ton CO_2).
- Financial cost F (US$).
- Energy consumed through import E_{IMP} (kJ).
- Carbon emission through import C_{IMP} (ton CO_2).

The 'local characteristics' consist of information that describes the area under study and includes yields for different food products (ton/ha), water requirements (m^3/ton), energy needs (kJ/ha or kJ/m^3), and other items, as listed in Figure 3. While the structure of the tool is generic, the local characteristic data are specific to the area under study and play an important role in defining the resource requirements for a given scenario.

Sustainability index

The tool allows the creation of multiple variations of scenarios. For example, while a given scenario could consume the least land, it might also be the most water intensive. The least water-intensive scenario could be the most financially demanding. A financially cheaper option might be one of the highest energy consuming scenarios, and so forth.

How do we know which scenario to choose? How do we decide on how much we can endure in terms of different resource requirements? How can the tool output be used in assessing proposed strategies? The answers are not straightforward. Assessment and comparison of scenarios can be accomplished through the calculation of a sustainability index that combines: (1) scientific input, which helps quantify system relations and physical capacities with (2) policy input, which reflects policy preferences and strategies.

The multidimensional nature of the framework and tool necessitates further understanding and analysis of the results. While the conceptual framework is generic in nature, analyses and solutions must be specific to the locale for which the solution is sought. Different governments, ministries or decision-making entities are likely to have different perspectives regarding the same set of results/costs for a proposed scenario and each needs to provide its respective inputs. The importance, or sensitivity, of each of the parameters (whether land, water, financial, energy or carbon) varies from one region to another. It could go far beyond choosing a solution that is least resource-demanding to one that could translate into a national strategy or vision, regardless of short-term costs. The local sustainability of a given scenario will be defined by calculating its 'sustainability index' following the two-step process below.

Creating 'resource indices' – requires scientific input

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Water index (WI) = W_i/W_a
Land index (LI) = L_i/L_a
Local energy index (EI) = E_i/E_a
Local carbon index (CI) = C_i/C_a
Financial index (FI) = F_i/F_a
Energy IMP index (E_{IMP} I) = E_{IMPi}/E_{IMPa}
Carbon IMP index (C_{IMP} I) = C_{IMPi}/C_{IMPa}

where index = amount of resource required by scenario/allowable capacity or limit.

In an effort to normalize the tool's output and identify any exceeded local limits, resource indices are calculated. Each index comprises that fraction of the acceptable amount of resource consumed by the proposed scenario. Scenarios with resource indices > 1 are less likely to be adopted: these are unfavourable in terms of local input demands. The local limits are part of the 'local characteristics' of the region under study. This process relies on a combination of scientific inputs and an understanding of the available resources; part of this process may involve consultation with stakeholders (i.e. ministries, governmental organizations, etc.): for example, the acceptable water limit (W_a) is a percentage of all available water resources that are allocated for agricultural production, and likewise, for L_a the percentage of arable land. Acceptable energy (E_a) represents a percentage of the energy allocated for the agricultural sector and its associated practices. Acceptable carbon limit (C_a) represents a maximum cap for emissions associated with agriculture and agriculture-related practices (water for agriculture, etc.); these might, in turn, be influenced by national carbon emission reduction commitments and respective quotas within the agricultural sector. Acceptable financial limit (F_a) represents that portion of the state budget associated with the scenario. E_{IMP} and C_{IMP} are less significant and could be more subjective, as these are related to energy consumption and carbon emissions in a global context through the transport of products. A step towards quantifying accurate acceptable limits would be through cross-sectoral stakeholder engagement representing different resource consuming sectors with the help of scientific input. This would facilitate quantifying specific quotas of resources to be used for executing different growth strategies across sectors.

Importance coefficient identification – reflects policy preference. It is critical to bring together scientific knowledge, on the one hand, and policy-making, on the other: both contributions must be captured in the process of identifying sustainable strategies. The input of policy-makers is needed after calculating the resource requirements for each scenario. This consists of identifying the relative importance of reducing each one of the resource requirements (water, energy, carbon, land, financial). In other words, what costs attributed with a given scenario are most important to reduce relative to others? Stakeholders, through focus groups, would assign an importance coefficient to each resource requirement, depending upon what their policies and strategies determine to be most important to be minimized. This would be reflective of national strategies and directions. The higher the importance coefficient, the more critical it is to adopt a scenario with a lower respective resource requirement. If reducing water footprint is a top priority, and of higher importance than other footprints, I_w (importance of reducing water requirement) would be higher. After that, the sustainability index of each proposed scenario is calculated. This index comprises the summation of the products of the 'resource indices' and their assigned 'importance coefficients'.

A lower assessment parameter index indicates that the given parameter is further from the maximum set limit, making the scenario more favourable. The lower the importance coefficient, the less important, and less sensitive, the given parameter. Thus, the scenario with the lowest score is the most sustainable, as defined by the decision-maker.

Scenario i:

$$\begin{aligned} S.I._i = {} & [WI_i(100\text{-}I_W) + LI_i(100\text{-}I_L) + EI_i(100\text{-}I_E) + CI_i(100\text{-}I_C) \\ & + FI_i(100\text{-}I_F) + E_{IMP}I_i(100\text{-}I_{EIMP}) \\ & + C_{IMP}I_i(100\text{-}I_{CIMP})]x100 \\ & I_W + I_L + I_E + I_C + I_F + I_{EIMP} + I_{CIMP} = 100 \end{aligned}$$

where 'I' is the importance factor assigned for resource, which reflects the relative importance of reducing the consumption of this resource in a scenario.

Framework and model assumptions and limitations

Throughout the study, several assumptions were made to simplify the complexity of the problem at hand. Different limitations also play a role in adding to the research complexity. Some examples follow.

- The food products assessed are currently limited to agricultural crops and do not include meat, dairy products, processed foods, etc.
- The existing tool assesses the environmental impact of a scenario only as reflected in its carbon emissions: no calculations are yet incorporated to quantify effects on water and soil quality.
- Information on current local characteristics (Figure 3) are based on estimations of locally collected data, and data representing similar environments. The ability to ensure locally measured data (water requirements, local yields, energy requirements, etc.) would provide more refined results.
- Relationships between system components are based on empirically based (not process-based) data.
- The current tool assumes linear relationships between systems, which may not reflect reality.
- The current tool does not capture future projections of prices, population increase, demand and resources. Rather, it simulates a static point in time with defined attributes.
- The current framework addresses resources needed for a proposed strategy from a national context, without taking into account the implications in a global context (except for energy and carbon emissions through import). Thus, the scope of the framework is national, and interconnections between different frameworks, representing different countries, needs to be further developed in order to create a global

picture that captures the comparative advantages of producing different products in specific locations. This would also allow better assessment of trade strategies.

- The current financial component in the tool calculates the cost of locally produced and imported food products, based on market price data. The financial cost of locally produced food products are represented by the market cost of products, after deducting a percentage profit margin for farmers. For imported food products, the cost of import consists of the 'cost insurance and freight', which does not include distribution costs. At this point, any capital investments required to execute a proposed scenario (building a new desalination plant, new power plant, etc.) must be assessed separately and then included in the financial cost. It is assumed that exports are sold at an average cost equal to the cost of import. Note that one of the main reasons the market price of local products is cheaper than imported products is because of high subsidies. The existing model also does not capture the financial costs associated with the use of different water and energy sources.
- Different risks are associated with the created scenarios assessed qualitatively in this study. Further work should set a specific methodology to quantify these risks.
- Input from science and policy-making is imperative as defined by the tool structure (Figure 3). A focus group, including a mix of scientists and decision-makers, is recommended to develop acceptable limits and importance coefficients while maintaining a high level of communication.
- The tool as it stands today (with its assumptions and limitations) helps create a rapid assessment by highlighting resource trends and alarms – and the relative sensitivity of these resource requirements to one another. Such analysis/rapid assessment would help highlight hotspots, and would hint towards the directions in which digging more vertically would be needed. This would then be done with the help of a more refined methodology and detailed data to assess different dimensions of the problem at hand more specifically.

WEF Nexus Tool evaluation: overall tool performance and sensitivity analysis

Overall performance

Governed by the presented methodology and tool structure, the user is able to create scenario variations by changing the self-sufficiency of food products, type of agricultural practices (open versus protected agriculture, when applicable), source of water, source of energy, and countries of import. Table 2 presents five scenarios for demonstration and further discussion. The scenarios range from full food self-sufficiency (%SS = 100) in scenario 1 to full dependency in scenario 5 (%SS = 0). The components of each scenario are also presented. These scenarios were created with the aid of WEF Nexus Tool 2.0 ©.

Data from Qatar are used to demonstrate the tool. These data consists primarily of data that represent the 'local characteristics' of the study area (Figure 3). The list of food products, chosen for demonstration purposes, includes tomato, eggplant, lettuce, carrot, watermelon, cucumber, potato and green onion: the list also represents elements in the Qatari diet, and items currently grown in varying levels of self-sufficiency. Preliminary assessment is used to evaluate the rationality of the results and assess the performance of the tool. For more detailed information on the tool methodology, datasets and data sources, see Daher (2012).

Figure 4 shows the tool results for the proposed scenarios. Water and land requirements are linearly affected by the change in percentages of self-sufficiencies and agricultural practice, decreasing as the self-sufficiencies of products decreases (cf. scenarios 1 and 5).

Table 2. Components of five different scenarios.

	Scenarios				
	1	2	3	4	5
Percentage of self-sufficiency of food products (%SS)	100	100	50	25	0
Percentage of food products grown in open agriculture conditions (%OpAg)	100	100	50	0	n.a.
Water source	100% GW	50% GW 50% RO	50% GW 50% RO	25% GW 50% MSF 25% RO	n.a.
Energy source	Diesel fuel	Diesel for GW NG for RO	Diesel for GW Solar for RO	Diesel for GW NG for MSF Solar for RO	n.a.
Countries of import	Status quo	Status quo	Status quo	Status quo	Status quo

Note: GW, 100% ground water; MSF, 100% multi-stage flash; NG, natural gas; RO, reverse osmosis; n.a., not applicable.

A similar, but less obvious, relation exists with regard to financial assessment, since we are accounting for the sum of the cost of local production and imported products. As the self-sufficiency of products decrease, the total financial costs increase. This comes as a result of the fact that the cost of imports, in almost every case, is higher than the cost of local production for the specific products. Financial cost is also considered as directly related to and affected by the change in self-sufficiency values. Note that the financial costs associated with the use of different energy or water sources across scenarios are not captured in this analysis.

The highest energy requirements are needed in scenario 2, which proposes full self-sufficiency with groundwater and desalination as sources of water. When comparing E_1 (energy for water) and E_2 (energy for food) values respectively, we see that total energy (E) is more influenced by E_1. When a reverse osmosis (RO) plant is introduced in scenario 2, E_1 greatly increased. Even when self-sufficiency was reduced to half (scenario 3), the energy requirement outweighed that of scenario 1, which included full sufficiency, but used ground water as the primary source of water. On the other hand, E_2, which is related to the energy required for local production, shows a trend that follows the decrease in self-sufficiency for scenarios 1–5.

Carbon emissions varied according to the type of fuel used in each scenario. While carbon emissions are mainly affected by the amount of energy consumed, type of fuel is the major player: the use of solar energy to power RO plants (scenario 3) is reflected in the C_1 overall carbon emissions plots. Since for the five scenarios the same type of fuel (diesel) is considered for all domestic practices (harvest, tillage, fertilizer production and transport), C_2 also follows a decreasing trend, reflective of the linear relation existing between it and the percentage self-sufficiency of food products.

E_{IMP}, the energy consumed through transporting imported food products, increases with decreased self-sufficiency. The amount of energy needed is directly related to the distance travelled by different methods of transport (air, sea, road), which in itself is highly affected by the choice of countries of import. In these scenarios, the countries of import were not varied, and thus the required energy for transport showed, as expected, an increasing trend with increase of imports. C_{IMP}, carbon emissions due to energy consumed through transporting

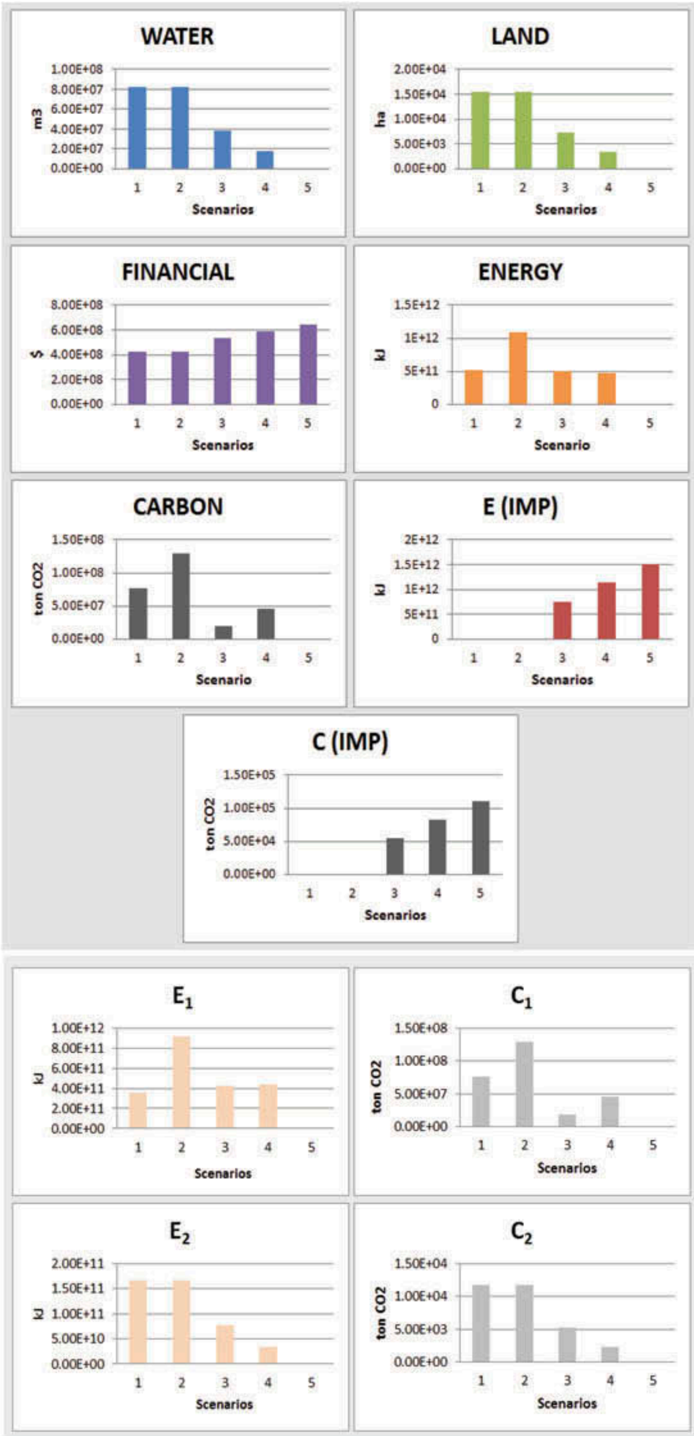

Figure 4. Tool output for the five input scenarios.

imported products, shows a similarly increasing trend as self-sufficiency declines. According to the demonstrated scenarios and results (trends), the tool is performing as expected.

Sensitivity analysis (relative sensitivity)

Further evaluation of the tool's performance is accomplished through sensitivity analysis of the different input parameters. There are three types of inputs: food, water and energy. The choice of % self sufficiency and %OpAg for the different food products determines how much land (ha), water (m^3), financial cost (US$) and energy in agriculture (E_2) are needed, as well as the respective carbon (C_2) emitted. The choice of countries of import affects how much energy is required through import (E_{IMP}) and the respective carbon emitted (C_{IMP}). After determining how much water is needed for the scenario, the sources of water need to be chosen. Based on the chosen water input, the energy needed for providing that water is quantified (E_1). Energy input constitutes choosing the sources of energy needed for water and indicates the carbon consequently emitted (C_1). Relative sensitivity is performed, and obtained through the following equation:

$$S_r = \left(\frac{O - O_b}{P_{b\pm\Delta} - P_b}\right)\frac{P_b}{O_b}$$

where S_r is the relative sensitivity; O is a new output; O_b is the output of the base scenario; P is a new parameter value; and P_b is the base parameter value in the base scenario.

Base Scenario I is presented in Table 3. In Assessment I – Food input, the % self-sufficiency and %OpAg will change for each food product. The main goal of this section is to assess the sensitivity of the tool.

Assessment I – Food input

Base Scenario I (Table 3). The % self-sufficiency (%SS) of the listed food products was changed by 15% and respective relative sensitivity on output was recorded. We notice the following from the relative sensitivity analysis for food input parameters in Figure 5:

Table 3. Base scenario food, water and energy inputs and output requirements (Assessment I).

INPUT							OUTPUT	
							W (m^3)	3.9E+0.7
							L (ha)	4947
Food products			Water sources		Energy sources		E_1 (kJ)	1.7E+11
	%SS	% OpAg		%		%	E_2 (kJ)	4.3E+10
Tomatoes	30	85	Ground water	100	Diesel	50	E (kJ)	2.1E+11
Eggplant	45	100			Natural gas	50	C_1 (ton CO_2)	2.8E+07
Lettuce	17	100			Wind	0	C_2 (ton CO_2)	3038
Carrots	20	100			Solar thermal	0	C (ton CO_2)	2.8E+07
Watermelon	25	100			Geothermal	0	F_{Local} (QAR)	1.3E+08
Cucumber	55	20			Nuclear	0	F_{IMP} (QAR)	3.5E+08
Potato	20	100			Biomass	0	E_{IMP} (kJ)	1.1E+12
Green onion	20	100					C_{IMP} (ton CO_2)	6E+0.9

Note: QAR = Qatari Riyals.

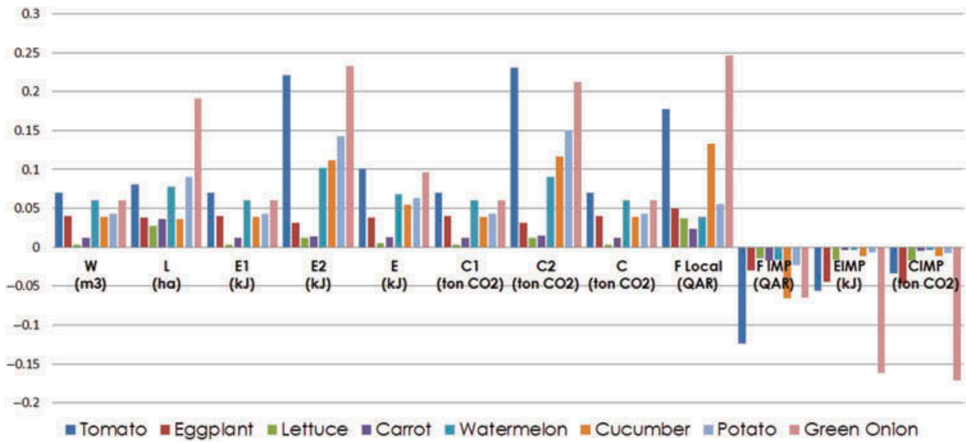

Figure 5. Relative sensitivity of a 15% change in self-sufficiencies of the different food products on output.

- The change in $\%SS_i$ affects all measured output parameters.
- There is an inverse relationship between $\%SS_i$ and F_{IMP}, E_{IMP} and C_{IMP} illustrated through the negative relative sensitivity values that exist among them. When the self-sufficiency of a chosen product increases, the cumulative costs of imports, energy consumed through transporting imports and carbon emitted as a result of the transport energy decrease.
- The relation between $\%SS_i$ and all output components affected by it are linear; this is validated by the identical relative sensitivity results obtained after increasing, then decreasing $\%SS_i$, over output components.
- The relative sensitivity of water (W), energy needed for supplying water for scenarios (E_1) and carbon emissions relative to E_1 (C_1) have a similar trend for the different food products. The relative sensitivities for change in $\%SS_i$ of food products on E_2 and C_2 have a similar trend for the respective list of products.

Among the food products under study, tomato and cucumber can be produced in Qatar under either open or protected agriculture.

- Figure 6 shows that the change in percentage of open agriculture (%OpAg) has no effect on local and import financial costs (F_{Local} and F_{IMP}), energy consumed through transport of imports (E_{IMP}) and respective carbon emitted (C_{IMP}): the relative sensitivity is zero, which validates the lack of relation between this parameter and output according to the tool structure. Ideally, the cost of locally produced crops varies with the type of agriculture. Further studies could be done to ensure that the effect of changing the type of agricultural practice is reflected in the local costs.
- Due to the linear relationship between percentage of food products grown under open agriculture conditions (%OpAg) and output components, increasing or decreasing the percentage gives similar relative sensitivity results for all outputs, thus validating the performance of the tool in that regard.

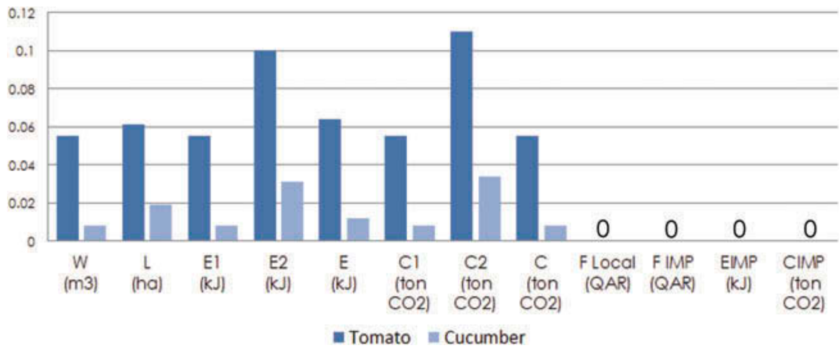

Figure 6. Relative sensitivity of the percentage of open agriculture for tomato and cucumber.

- Figure 5 shows that the relative sensitivity of changing the percentage of tomatoes grown in open agriculture (%OpAg of tomatoes) is higher than changing that of cucumber on outputs. That is a result of the higher tomato consumption (tons) for year 2010.

Assessment II – Water input

In Assessment II, the source of water was changed *ceteris paribus*, where II-A is 100% reverse osmosis (RO) desalination, II-B is 100% multi-stage flash (MSF) desalination, II-C is 100% multi-effect distillation (MED), and II-D is 100% treated waste water.

Base Scenario II (Table 4). The change in the source of water only affects E_1 and C_1. No change in any other output was recorded. The most energy-consuming and carbon-emitting scenario is II-B (Figure 7). It uses 100% of water from desalinated MSF. The least energy use was recorded for scenario II-D. Moreover, E_1 and C_1 follow a similar trend due to the linear relation between both parameters.

Table 4. Base scenario food, water, and energy inputs and output requirements (Assessment II).

INPUT							OUTPUT	
							W (m^3)	3.9E+07
							L (ha)	4947
Food products			Water sources		Energy sources		E_1 (kJ)	1.7E+11
	%SS	% OpAg		%		%	E_2 (kJ)	4.3E+10
Tomatoes	30	85	Ground water	100	Diesel	100	E (kJ)	2.1E+11
Eggplant	45	100			Natural gas	0	C_1 (ton CO_2)	2.8E+07
Lettuce	17	100			Wind	0	C_2 (ton CO_2)	3038
Carrots	20	100			Solar thermal	0	C (ton CO_2)	2.8E+07
Watermelon	25	100			Geothermal	0	F_{Local} (QAR)	1.3E+08
Cucumber	55	20			Nuclear	0	F_{IMP} (QAR)	3.5E+08
Potato	20	100			Biomass	0	E_{IMP} (kJ)	1.1E+12
Green onion	20	100					C_{IMP} (ton CO_2)	6E+0.9

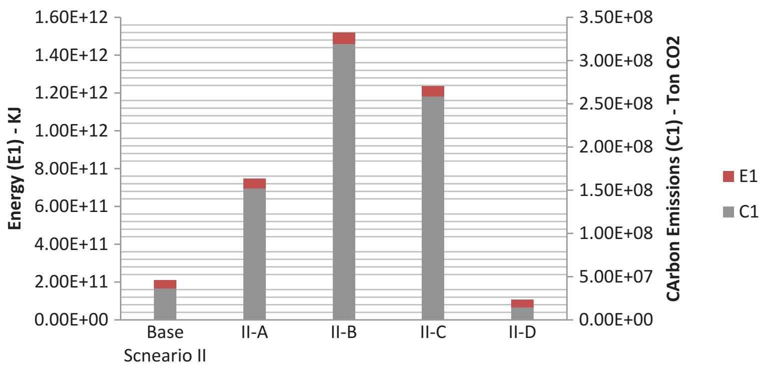

Figure 7. Energy requirement E_1 and respective carbon emissions C_1 for Assessment 2 scenarios.

Assessment III – Energy input

Base Scenario III. Base Scenario III (= diesel; III-A = natural gas; III-B = wind; III-C = solar thermal; III-D = geothermal; III-E = nuclear; and III-F = biomass) is the same as Base Scenario II, the only thing changing is the source of energy (the self-sufficiencies, type of agriculture and water source (100% ground water – GW) remain the same). The reason only C_1 changes is because gasoline (petrol) was assumed for other local production energy demanding practices (fertilizer production, tillage and harvest which all contribute to C_2). Diesel is most carbon emitting, followed by natural gas (Figure 8).

The main building block for calculations in the tool is yearly consumption values for the chosen food products (ton/year). A 15% increase in tomatoes is not equal to a 15% increase in eggplant (tons). For that reason, we do not necessarily see a similar trend between water requirements (m^3/ton) for the different food products and their sensitivities (Figure 5). In Assessment I, the analysis is based on 2010 consumption values for food products; the water requirement is most sensitive to change in the %SS of tomato. Green onion ranked highest in terms of land use sensitivity, while the energy needed for local food production (E_2) and local carbon footprint (C_2) are most sensitive to change in tomato and green onion production. Local financial cost is also most affected by both products. Having tomatoes and green onions highest, in terms of consumption (tons) for

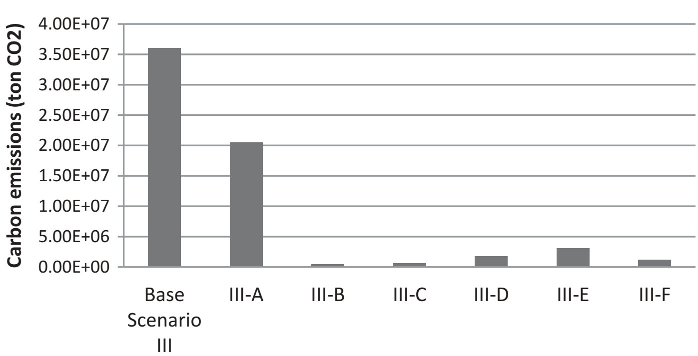

Figure 8. Carbon emissions C_1 for Assessment 3 scenarios for the energy consumed for securing needed water for the scenarios.

year 2010, any change in the choice of producing them locally has the greatest impact on different requirements. Assessment 2 evaluations support the fact that changes in sources of water and technologies for the scenario affect the energy use and carbon emissions (Figure 7). Future improvements to the tool should include the extra costs that come with adopting different technologies. Assessment 3 evaluations show that C_1 is the only changing output when the type of fuel used for securing water for the scenario is changed. The overall performance of tool is as expected. The current trends portray the framework structure that is, itself, dynamic and in need of further advancement.

Case study: results and discussions

In 2010, 41 crops were reported by the General Department for Agricultural Research & Development, Ministry of Environment as locally produced in different proportions. The analyses in the first part of this section include scenarios using the eight food products identified above; afterwards, a separate analysis of the potential of growing the staple cereal wheat will be discussed.

Figure 9 depicts the situation in Qatar, based on the data available in 2010. The average self-sufficiency of the eight food products is 15%. Among these, only tomatoes and cucumbers are produced in both open and protected conditions; all others are produced with open agriculture. Ground water is the main source of water for irrigation, natural gas the main source of energy and imports are primarily secured from 15 countries. The results (Figure 9) show the requirements needed for the actual 2010 scenario. Because the study is limited to eight food products, comparing a scenario's requirements with maximum acceptable national capacities has only limited value.

The presented food products are among those currently produced and expected to have an increase in their self-sufficiency. Thus, a hypothetical self-sufficiency increase scenario for the products and an assessment of the expected resource requirements allows identification of the most critical resources when adopting decisions about increased food self-sufficiency. Each of the eight food products had a different self-sufficiency value for 2010. The graphs shown in Figures 9 and 10 represent the percentage change in the required resources resulting from an increase in the self-sufficiency of each of the products. Figure 9 shows how much more resources would be needed if the self-sufficiency of each product (tomatoes, cucumbers, water melon, green onion, lettuce, potato, eggplant and carrots) was increased by an increment of 10 percentage points (i.e. if current self-sufficiency of tomatoes is 15%, in this scenario it is raised to 25%). In this case:

- The overall self-sufficiency increase is 25%. However, this 25% increase in self-sufficiency requires 82% more water, 153% more land, 82% more energy for supplying water and 97% more energy for local food production. A total of 82% more carbon will be emitted as a result of energy consumed for supplying water, and 93% more carbon emitted as a result of food production. Producing 10% more of each of the food products would increase the overall financial cost by 78%. The gross total import cost will decrease by 12%, and the energy consumed and carbon emitted through transporting imported food products would decrease by 11%.
- As the percentage of self-sufficiency increases, there is a linear trend in resource requirements due to the linearity of the tool relations (which is not necessarily reflective of reality).
- Land demand increases as the slope becomes steeper, and is followed by increases in energy required and carbon emission for local food production; the outcome is

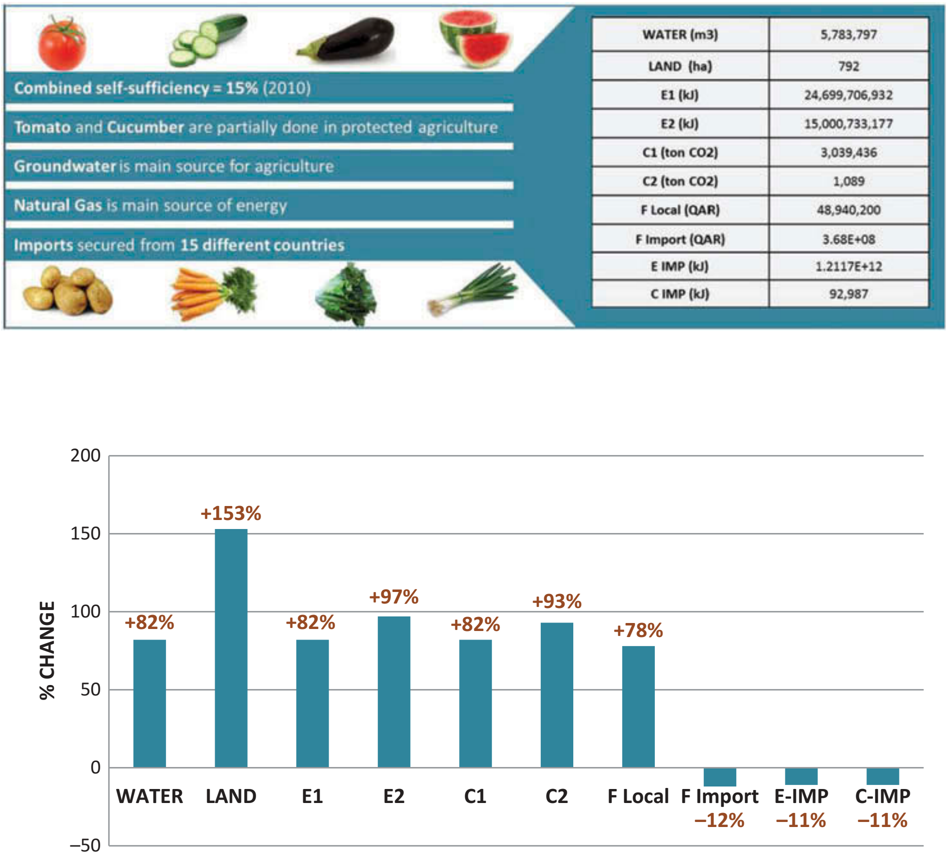

Figure 9. Resource requirement for a 2010 scenario (input data from the Qatar National Food Security Programme – QNFSP) and percentage change in the resource requirements as a result of a 10% increment in self-sufficiency.

similar for water, energy and carbon used for water production. Based on the preliminary projections of the study sample in Qatar, the following are possible conclusions.

- Land is the most sensitive resource requirement among the output parameters. Therefore, it is key to invest in research and consolidate efforts towards improving local yields (ton/ha). Detailed soil suitability mapping for potential food products needs to be created in order to choose the optimum locations for producing the specific food products. Cultivation technologies reduce or minimize land requirements (hydroponics, more products to be grown in green house environments, etc.) should be investigated.
- Energy requirement and carbon footprint for food production rank second after land requirement. Investing in more efficient machinery for tillage, harvest and transport should be considered. (These recommendations are based on assumptions for tillage, harvest, transport and fertilizer production. When local data are collected for these items, more accurate conclusions can be derived.) Gasoline was used as a fuel for these practices. Investment in machinery that consumes less carbon-emitting fuels should be considered as a way to mitigate the increase in energy needs and carbon emissions.

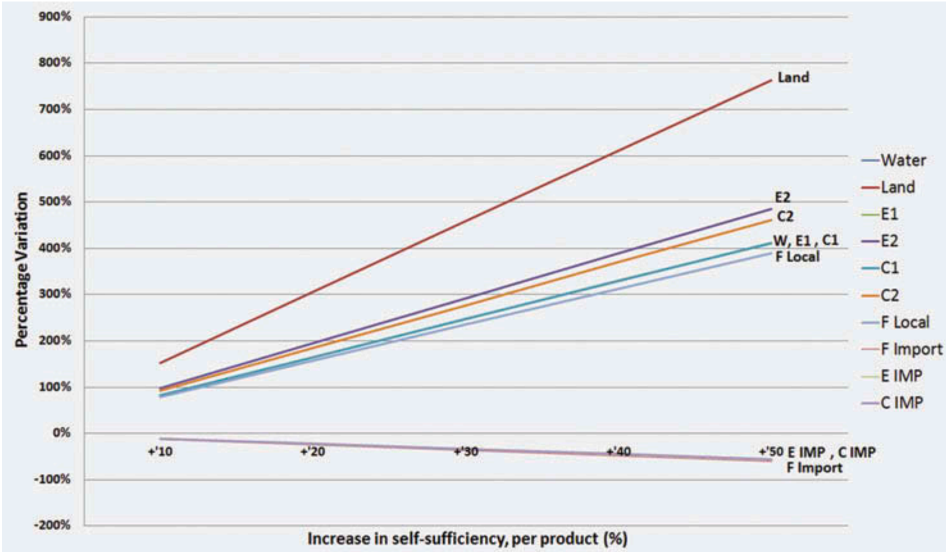

Figure 10. Percentage change of resource requirements as a result of the percentage change in self-sufficiency per food product.

Water, energy for water and respective carbon footprint

The current scenario relies on groundwater for irrigation. With the current replenishment rates in Qatar, this reliance on groundwater could lead to catastrophic consequences. Any plan to increase food self-sufficiency should be supported by the ideas listed below:

- Create a plan for investing less water by demanding new technologies and irrigation techniques.
- Rely on alternatives to groundwater for securing water for food production, e.g. dedicate a portion of desalinated water for this purpose. If current desalination capacities cannot hold the extra demand, investing in upgrades should be considered. Due to the direct relation between securing water, energy consumed and carbon emitted, low-energy-low-carbon-emitting options should be adopted.
- Explore potentials of different renewables to fuel the technologies needed to secure the required water.
- Assess the financial costs of investment in these new technologies to increase current capacities (not currently captured by tool).

F_{Local} *and* F_{IMP}

The local financial cost of food production is the least sensitive of the other resource requirements. Any anticipated increase in financial costs needs to be properly integrated into financial planning. With increasing self-sufficiency, the financial costs of importing food products decreases. The decrease is at a lower rate than the increase of local financial costs due to the fact that imported food products are of higher QAR/ton value.

E_{IMP} and C_{IMP}

With increasing local self-sufficiency, the energy and carbon for imports decreases.

Most sensitive does not necessarily mean most critical!

In the previous discussions, land was found to be the most sensitive to an increase in self-sufficiency. That does not mean that this is the bottleneck. Having to secure 84% more water for a 10% increase in self-sufficiencies could be more critical than having to secure 153% more land for the same scenario. Defining the bottleneck depends on the foreseen planning in terms of upgrading current capacities and investing in new technologies.

What if Qatar decides to grow wheat?

In the early 1960s, the Kingdom of Saudi Arabia started growing wheat locally. Production reach its peak in the early 1990s with 4 MMton/year (Index Mundi, 2014). That practice consumed great quantities of ground water resources, most of which were non-renewable. In developing a food security plan, wheat has significant strategic importance among the staple cereals. According to UN Comtrade (2014), around 400 000 tons of wheat were imported into Qatar in 2010. Based on the previous analysis for base year 2010 for the eight food products, while keeping all self-sufficiencies the same, the following analysis measures the percentage change in resource needs after introducing a local production of 10% of the consumed wheat (Figure 11).

The amount of water needed would increase by 614%. Energy for water and respective carbon emissions will similarly increase. It is significant that land proved a less sensitive resource than water for the introduced 10% of locally produced wheat, due to the high yields in centre-pivot irrigated wheat, estimated to be 6 ton/ha (International Maize and Wheat Improvement Center, 2014). Nevertheless, this analysis further demonstrates the amount of additional resources needed for such a decision within a food security strategy.

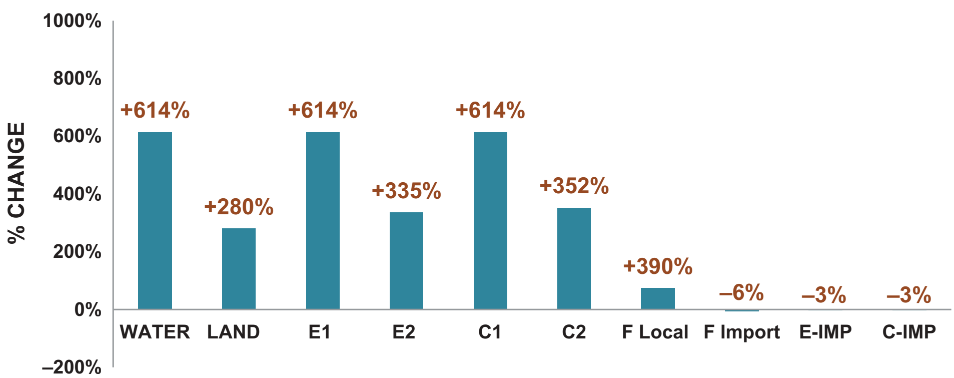

Figure 11. Percentage change in resource needs as a result of producing 10% of consumed wheat in year 2010 while keeping the other 8 products at 2010 self-sufficiency values.

Conclusions

Water, energy and food are highly interconnected and their interlinkages need to be reflected in the planning and decision-making landscapes governing the management of these resources. Defining local sustainability through input from involved stakeholders, as well as from the scientific and policy-making arenas, is key to proper planning and management. This paper presented a framework for a tool that reflects the interconnectedness of these core resources. The demonstrated tool is dynamic. It offers an assessment of the resource demands for different scenarios that could be used as a foundation for enforcing new guided management strategies. The tool also offers a platform structured to bring together input from science and policy-making to converge toward set goals. Further work needs to be done to improve the existing functions within the framework, as well as on building the ability to create scenarios that are energy or water focused. Modifications to the framework and tool would then be made in response to specific critical questions the user needs to answer.

Based on the Qatar case study, land is highly sensitive to variations of food self-sufficiency scenarios, as are water, energy and others. Special focus needs to be directed towards improving yields of locally produced food products, as well as investing in research for crops most suitable for growth in dry areas. Such approaches might not be the most economically viable when compared with entirely relying on imports instead, but would be attractive in the sense of providing additional security in the broader sense. Greater emphasis needs to be made on developing robust trade strategies to cover the main country food needs. Identifying countries of low risk (in terms of ability to maintain export, low health hazard risk, etc.) and diversifying the sources of import per food product are also important elements of such strategy.

The WEF Nexus Tool 2.0 and WEF framework provide a first building block that needs to continue evolving in order to provide better the needed analytics for such complex questions involving systems that are tightly interconnected and highly dynamic in a non-stationary world of constantly changing externalities.

Acknowledgements

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Note

1. WEF Nexus Tool 2.0 © is a public tool developed by Daher and Mohtar in 2012. The tool can be accessed at wefnexustool.org/. Users can create their own account and build scenarios to assess different resource allocation strategies.

References

Bonn Conference (2011). Understanding the nexus. Retrieved from http://www.water-energy-food.org/en/news/view__255/understanding-the-nexus.html

Commonwealth (2009). Biofuel subsidies and food prices in the context of WTO agreements. Retrieved from http://www.thecommonwealth.org/files/214119/FileName/THT63BiofuelSubsidiesandFoodPrices.pdf

Daher, B. (2012). Water, energy, and food nexus: A basis for strategic planning for natural resources. Retrieved from http://docs.lib.purdue.edu/dissertations/AAI1529829/

FAO (2013). An innovative accounting framework for the food-energy-water nexus Retrieved from http://www.fao.org/docrep/019/i3468e/i3468e.pdf
FAO (2014). Walking the nexus talk: Assessing the water–energy–food nexus in the context of the sustainable energy for all initiative. Retrieved from http://www.fao.org/3/a-i3959e.pdf
GIZ (2012). Nexus approach highlighted. Retrieved from http://www.water-energy-food.org/en/news/view__453/nexus_approach_highlighted.html
GWSP (2014). Sustainability in the water–energy–food nexus, Bonn, Germany, 19–20 May 2014. Retrieved from http://wefconference.gwsp.org/fileadmin/WEF_Conference/Summary_Part_II.pdf
IEA (2012). World energy outlook 2012. Retrieved from http://www.worldenergyoutlook.org/publications/weo-2012/
IEA (2013). World energy outlook 2013. Retrieved from http://www.worldenergyoutlook.org/publications/weo-2013/
Index Mundi. (2014). Saudi Arabia wheat production per year. Retrieved from http://www.indexmundi.com/agriculture/?country=sa&commodity=wheat&graph=production
International Maize and Wheat Improvement Center (2014). Wheat production and use: Saudi Arabia. Retrieved from http://wheatatlas.org/country/production/SAU/21011
IRENA (2013). MENA renewables status report. Retrieved from http://www.ren21.net/Portals/0/documents/activities/Regional%20Reports/MENA_2013_lowres.pdf
IRENA (2015). Renewable energy and the water, energy and food nexus. Retrieved from http://www.irena.org/documentdownloads/publications/irena_water_energy_food_nexus_2015.pdf
KTH (2013). CLEWs – climate, land, energy and water strategies to navigate the nexus. Last accessed on July 2, 2014. Retrieved from http://www.kth.se/en/itm/inst/energiteknik/forskning/desa/researchareas/clews-climate-land-energy-and-water-strategies-to-navigate-the-nexus-1.432255
McKinsey & Co. (2009). Charting our water future: Economic frameworks to inform decision making. Retrieved from http://www.mckinsey.com/App_Media/Reports/Water/Charting_Our_Water_Future_Exec%20Summary_001.pdf
Mohtar, R. H., & Daher, B. (2012). *Water, energy, and food: The ultimate nexus. Encyclopedia of agricultural, food and biological engineering* (pp. 1–15). (2nd ed.). Abingdon, UK: Taylor & Francis: DOI:10.1081/E-EAFE2-120048376
OECD-IEA. (2010). *Sustainable management of water resources in agriculture*. OECD Studies on Water. http://doi.org/10.1787/9789264083578-en
SEI (Stockholm Environment Institute). (2011). Understanding the nexus. Background paper for the Bonn 2011 Nexus Conference. Retrieved from http://sei-international.org/mediamanager/documents/Publications/SEI-Paper-Hoff-UnderstandingTheNexus-2011.pdf
SEI (2013). Long range energy alternatives planning system. Tool found on: http://sei-us.org/software/leap
SEI (2014). Water evaluation and planning. Tool found on: http://www.weap21.org/index.asp?action=200
UN Comtrade (2014). Retrieved from http://comtrade.un.org/
UNESCO (2014).Water and energy. Volume 1. The United Nations World Water Development Report 2014. Retrieved form http://unesdoc.unesco.org/images/0022/002257/225741E.pdf
Weitz, N., Nilsson, M., & Davis, M. (2014). A nexus approach to the post-2015 agenda: Formulating integrated water, energy, and food SDGs. *SAIS Review of International Affairs*, *34*(2), 37–50. http://doi.org/10.1353/sais.2014.0022
World Bank Report (2009). Retrieved from http://siteresources.worldbank.org/EXTAR2009/Resources/6223977-1252950831873/AR09_Complete.pdf
World Economic Forum (2011a). Water security: The water-energy-food-climate nexus. Retrieved from http://www.weforum.org/reports/water-security-water-energy-food-climate-nexus
World Economic Forum (2011b). Global risks 2011. World economic forum. January 2011. Retrieved from http://reports.weforum.org/global-risks-2011/