Water, energy and food nexus: A basis for resource planning

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ABSTRACT

As a result of the growing recognition of the intimate interconnectedness between water, energy, and food (WEF) in science and decision making communities worldwide, a paradigm shift has forced itself into the management approach governing these resources and is causing a shift from silos to more integrative approaches. This paper introduces a new scenario-based framework and set of methodologies that define the interlinkages between these integrated resources and provide explicit quantifications for those relations. Based on the introduced framework, the paper will also present a new WEF Nexus modelling tool that evaluates different national resource allocation strategies through quantifying requirements for proposed scenarios. Qatar is a country planning its food security strategy within the constraints of its challenging dry land environment. It presents a unique case for assessing the implications of different proposed directions and evaluating the feasibility of their implementation. Data from Qatar is used to evaluate the tool's structure and overall performance. Preliminary analysis of the food security system in Qatar shows that increasing the food self-sufficiency by 10% for eight chosen food products, increases land requirement by 153%, and water and energy requirements by more than 80%. The land requirement component proves to be most sensitive, beyond water, energy, financial requirements and carbon emissions. "Sustainability Index" criteria is introduced as a means for identifying locally favorable scenarios, guided by both scientific and policy inputs. The presented WEF nexus framework and tool provide a dynamic model for systematic integration of resources and a common platform for scientists and policy makers to identify sustainable national resource allocation strategies.

Key words: resource management, tool modeling, integrated policy, sustainability index, water and food security, nexus

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NOMENCLATURE

GW= Groundwater

RO= Reverse Osmosis

MSF= Multi-Stage Flash

MED = Multiple-Effect Distillation

NG= Natural Gas

$\%SS_i$= Percentage food self-sufficiency of product i

$\%OP\ Ag_i$= Percentage of product i produced in open agriculture

E_1 = Energy requirement for providing water (kJ/m^3)

E_2 = Energy requirement for local food production (kJ/ha)

C_1 = Carbon emissions due to energy consumed for providing water needs for scenario (ton $CO_2/kJ/m^3$)

C_2 = Carbon emissions due to energy consumed for local food production for scenario (ton $CO_2/kJ/ha$)

DPC= Domestically produced and consumed food products (ton)

DPE= Domestically produced and exported food products (ton)

IMP= Imported food product (ton)

WR= Water Requirement (m^3/ton)

W_i = total water requirement for scenario i

L_i = total land area required for scenario i

E_i = total local energy required for scenario i

C_i = total local carbon emitted by scenario i

$F_{i\ =}$ total finances for scenario i = $F_{local} + F_{Import}$ (local and import)

$E\ IMP_i$ = total energy required for import of products for scenario i

$C\ IMP_i$ = total carbon emitted through import of products for scenario i

W_a = total max acceptable water extracted and produced by available water resources for agricultural production

L_a = max acceptable/arable local land use

E_a = max acceptable energy use = a cap could be put on max energy generation and use for agricultural production. It is influenced by current capacities, and decision of upgrade.

C_a = max acceptable carbon emissions = a cap put by a government to cut carbon emitted

F_a = max acceptable limits for expenditures to supply food locally and through imports

$E\ IMP_a$= max energy consumed through transporting imported food products

$C\ IMP_a$ = max carbon emitted through transporting imported food products

I_W = Importance factor assigned for the water assessment parameter

I_L = Importance factor assigned for the land assessment parameter

I_E = Importance factor assigned for the energy assessment parameter

I_C = Importance factor assigned for the carbon assessment parameter

I_F = Importance factor assigned for the financial assessment parameter

$I_{E\ IMP}$ = Importance factor assigned for 'energy for global transport' assessment parameter

$I_{C\ IMP}$ = Importance factor assigned for 'carbon emissions due to global transport' assessment parameter

I.   INTRODUCTION

The unprecedented increase in global population, coupled with growth of middle class societies that are gaining extra purchasing power, puts resources under stress. Factors including climatic changes, changing economies, international trade, governance, health and environmental protection concerns, play a role in magnifying or reducing these stresses. In the absence of systemic management strategies, these resources are being depleted and will not suffice for the surging demand. Future projections for water sufficiency, water quality, food sufficiency, energy availability, soil and air quality among others, are alarming. All these alarms head into one major conclusion- a starting point; business as usual is no longer viable. As silver bullet solutions cease to exist, there is a need for a fundamental shift in the way we understand and manage our resources. While the shift from a silo approach to a more integrative one is being promoted on global stages, progress is still fragmented and focused on specific angles of the nexus.

Literature Review

Water, energy, and food are highly interconnected systems. Food production requires water; water pumping, treatment, and transport require energy; and energy production requires water (Mohtar and Daher, 2012). The three systems are also affected by forces which contribute to exacerbating or reducing the stresses among the interconnected systems. Some of these forces include changing economies, governance, climate change, population growth and trade (Figure 1). National strategies governing the management of each of these systems are often developed independently, and thus, fail to consider the existing interconnections amongst those systems. The result is often conflicting strategies competing for the same resources. Nexus discussions are gaining thrust in policy and science arenas over the past few years. There is greater awareness to the need of integrative planning amongst the involved entities.

Water, energy, and food were first introduced as a "nexus" during the World Economic Forum Annual Meeting in 2008 (World Economic Forum, 2011). The nexus was also identified as one of the Global Risks in 2011 (WEF, 2011). Afterward, in Bonn (2011), a key milestone was introduced: looking at water, energy, and food securities in an integrative manner. One major opportunity for action resulting from the Bonn conference focused on ensuring that the interdependency between water, energy, and food security is "explicitly identified in decision making" (Bonn Conference, 2011). Three years later during the "Sustainability in Water-Energy-Food Nexus" Conference (Bonn, 2014), there was a call for action from the policy making and research communities worldwide: to develop strategies that address a comprehensive nexus approach. The Sustainable Development Goals (SDGs) narrative offered an additional call for integrating the nexus approach (GWSP, 2014). UN Secretary General Ban Ki-moon highlighted the use of a nexus approach while urging the inclusion of environmental, social and economic dimensions (GIZ, 2012). The importance of looking at the integrative management of resources is also

prevalent in climate change discussions. UNFCCC Executive Secretary Christina Figueres, in the Conference of Parties (COP18), highlighted the importance of the food-water-energy nexus, describing it as the "human face" as well as solution to climate change (WMO, 2012).

Current stresses facing our global community, together with the interrelated projected challenges, are the main drivers moving the water-energy-food nexus discussion. At the current rate of population growth, the agricultural sector faces the challenge of doubling food production by 2050 (OECD, 2010). About 71% of current world water withdrawals are attributed to the agricultural sector (McKinsey, 2009). By 2050, we expect a 55% increase in global water demand to address growing demand from manufacturing, electricity generation, and domestic use; the projected outcome is that more than 40% of the global population will be living with severe water stress (UNESCO, 2014). In 2010, the energy sector consumed 15% of the global water withdrawals (IEA, 2012), while contributing to two-thirds of the global greenhouse gases (IEA, 2013). In turn, securing different sources of water carries a high energy cost through desalination, pumping and treatment. In the MENA region, where 38% of global desalination takes place, electricity demand attributed to desalination is expected to increase to 122 TWh in 2013, tripling 2007 levels (IRENA, 2012). As energy demand rises, the search for alternative energy sources becomes more critical, and shifting to alternative energy sources might come with unintended consequences that directly impact other systems. Between 2003 and 2007, two thirds of the increase in global maize production was used for biofuel production (World Bank, 2009), setting off the global food price hike of 2008, which was highly attributed to biofuel subsidies, among others (Commonwealth, 2009).

Securing the water, energy, and food needs for current and future generations, while maintaining a healthy environment within successful, sustainable economies is a complex challenge. Major power lies in the hands of policy makers, who govern different parts of this puzzle. The scientific sphere has made progress in term of understanding and quantifying the volume of the challenges that lie ahead, but how will this knowledge be transferred into the policy sphere to yield informed decisions? Decision makers currently lack the proper tools to allow for accounting requirements for different resource allocation strategies and help understand the trade-offs which exist amongst the different systems. Tools that address different aspects of the nexus have been developed and these include WEAP (SEI, 2014), LEAP (SEI, 2013), MuSIASEM (FAO, 2013), CLEWS (KTH, 2013) and others. WEAP (Water Evaluation And Planning) takes an integrated approach to water resource planning, while LEAP is a tool directed for energy policy analysis and climate change mitigation assessment. MuSIASEM offers a method to characterize flows of different systems within society. CLEWS further develops an integrated systems approach to determine the interaction between different interconnected sectors. These tools offer

important advances in terms of analyzing separate resource systems, as well as offer different methods for looking at different flows among them.

There is a need for a generic, holistic framework that regards the systems' existent interlinkages and that offers decision makers a solid foundation for debate, discussion, and action.

Objectives

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

Specifically, the objectives of the paper are to:

1. Develop a scenario-based integrated framework and an application tool based on that framework which offers an explicit quantification of the existent interlinkages between nexus components and affecting externalities;

2. Evaluate the tool's performance through assessment of its functionality and output, as well as performing sensitivity analysis to its parameters;

3. Demonstrate the tool's utility as a decision making guide in a case study for Qatar.

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

II. METHODOLOGY

A. Conceptual scenario-based framework

Figure 2 shows a generic conceptual representation of the existent interconnections between the water, energy and food systems. The following framework starts by identifying the existing nationally consumed food products. A portion of these products are 'domestically produced and consumed' (DPC), while others are imported (IMP). Food products could also be domestically produced and exported (DPE). A decision made comes with different associated costs and risks depending upon shifts in the scenario to rely more on local production, or on imports. Based on a proposed food profile, national water and energy portfolios need to be decided within the context of respecting the systems' interconnections. The local feasibility of any proposed scenario can then be assessed.

Importing food products carries additional financial requirements as a result of additional transport costs. Transporting products through land, air, or sea requires energy: carbon is emitted. Countries that rely heavily on food imports face different risks, that are mainly characterized by the inability of current exporting sources to maintain supply, and vulnerability to global food price fluctuations. Risk in this

context also carries a political dimension, as well as a health threat element. Through import, on the other hand, a country could be saving in the costs of its local land and water resources. Alternatively, aiming to reduce reliance on imports in favor of increased **reliance on local food production** requires a process of profound understanding of the potential of the nation's local resources and the readiness of the country to withstand requirements accompanied with such a shift in securing food needs.

Considerations for local agricultural expansion include the following:
- **Water**
  - Quantify water requirements for a proposed food self-sufficiency scenario, controlled by the type of agriculture and technology.
  - Study and quantify available conventional and non-conventional water sources allocated for agricultural practices.
- **Land**
  - Quantify land requirements for a proposed self-sufficiency scenario
  - Allocate and quantify areas of land suitable for growing proposed products
- **Financial**
  - Quantify the cost of local production, which may include capital costs as well as production and operational costs.
- **Energy**
  - Quantify energy needs, which are divided between securing water –through pumping, treatment, or other- and the energy needs for agricultural processes; tillage, harvest, fertilizer production, and local transport. Energy requirements will be determined by the used technologies and their 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 used energy and technology.
  - Local climate determines the type of products which could be grown, and time of year and type of agriculture optimal for their growth.

B. 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 in order to properly assess

different scenario variations and guide decision making. Figure 3 demonstrates the flows that exist between water, energy, and food based on the presented conceptual framework.

Through proposing a food self-sufficiency scenario, domestically produced and consumed (DPC), domestically produced and exported (DPE), and imported (IMP) food products are quantified **(ton)**. While imports are secured through trade with global markets, DPC and DPE consume local resources. Depending on the types of food products and their respective local yields **(ha/ton)**, land requirement is defined **(ha)**. Financial requirements needed for growing the food products **($/ton)**, as well as profits made, depend on the type of products produced.

The amount of water needed **(m^3)** for a proposed self-sufficiency scenario depends on the water requirements WR **(m^3/ton)** of the types of food products grown locally. It is primarily affected by the type of agriculture and technology. The water needed for growing food products in open field agriculture versus greenhouses could widely vary. Water requirement is also highly affected by adopted irrigation methods. 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 for securing water, energy is also required for food production processes - E_2 **(kJ/ha).** Energy is secured through different available sources, and, depending on the energy need and source, the carbon footprint is quantified C_1 **($ton\ CO_2/m^3$)** and C_2 **($ton\ CO_2/ha$)**. In a global perspective, energy is also needed for transporting imported food products- E_{IMP} **(kJ/ton).** Respective carbon is emitted C_{IMP} **($ton\ CO_2/ton$).**

C. Tool Structure (WEF Nexus Tool 2.0)[1]

After defining the interconnections between the three systems, this section will introduce the 'WEF Nexus Tool' structure (figure 4) which allows for creating and assessing different scenarios, consisting of inputs that reflect national food, water, and energy strategies.

The user creates a scenario through choosing the following:
- self-sufficiency (%SS) of food products in a selected national food basket (eg. %SS of tomato 50%, %SS of cucumber 20%)
- percentage of grown food products under open agriculture conditions (%OP AG) (versus protected agriculture/greenhouses) for each (eg. 30% of tomatoes produced in open conditions, while 70% of are produced in greenhouses)

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[1] WEF Nexus Tool 2.0© is a public tool which can be accessed at wefnexustool.org Users create their own account and build scenarios to assess different resource allocation strategies

- percentages for each of the different water sources for the selected scenario (eg. 30% desalination, 70% Groundwater)
- percentages of energy sources for the scenario (eg. 30% fuel oil, 20% wind, 50% solar)
- percentage supplied and sources of countries for the imported food products (eg. 30% of imported tomatoes from Jordan, 70% from Lebanon)

Using the 5 scenario inputs above, and based on the local characteristics of the area under study (figure 4), the tool assesses the 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(E1) and energy for local food production(E2)
- Local carbon footprint C=(C1+C2) **($tonCO_2$)**
- Financial cost **F($)**
- Energy consumption through import **E-IMP(kJ)**
- Carbon emission through import **C-IMP(ton CO_2)**

The 'local characteristics' consist of information which describe 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 4. While the structure of the tool is generic, the 'local characteristic' data is specific to the area under study and plays a big role in defining the resource requirements for a scenario.

- **Sustainability Index**

The tool allows the creation of multiple variations of scenarios. While a proposed scenario could consume the least land, for example, 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.

The user is then able to better identify the local feasibility of a variety of options that prove suitable for adoption. How do we know which scenario to choose? How do we decide how much are we able to endure in terms of costs for different parameters? How could the output of the tool be used in assessing proposed strategies? The answers to these questions are not straight forward. Assessment and comparison of these scenarios is accomplished through the calculation of a sustainability index which combines: a)

scientific input, helps quantify system relations and capacities and b) **policy input**, reflecting policy preferences and strategies.

The multidimensional nature of the framework and tool necessitate further understanding and analysis of the results. While the conceptual framework is generic in nature, analyses and solutions need to 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 need to provide their input. The importance, or sensitivity, of each of the parameters (whether land, water, financial, energy, carbon) vary from one region to another. It could go far beyond choosing a solution that is least resource demanding, to a choice that would translate a national strategy or vision, regardless of short term costs. The local sustainability of a scenario will be defined by calculating its "sustainability index" following the two-step process below:

1- **Creating "resource indices" – Scientific Input**

$$\text{Water Index} = WI = W_i / W_a$$
$$\text{Land Index} = LI = L_i / L_a$$
$$\text{Local Energy Index} = EI = E_i / E_a$$
$$\text{Local Carbon Index} = CI = C_i / C_a$$
$$\text{Financial Index} = FI = F_i / F_a$$
$$\text{Energy IMP Index} = EIMP\ I = E\ IMP_i / E\ IMP_a$$
$$\text{Carbon IMP Index} = CIMP\ I = C\ IMP_i / C\ IMP_a$$

In an attempt to normalize the tool's output and identify any exceeded local limits, resource indices are calculated. Each index comprises the fraction of the acceptable amount of resource consumed by the proposed scenario. The scenario with resource indices >1 would be less likely to be adopted. These would be scenarios that are unfavorable according to local input. Identifying the local limits is part of identifying the 'local characteristics' of the area of study: a process that relies on a combination of scientific inputs and understanding the availability of different resources. It could also be identified through consultation with stakeholders (i.e. ministries, governmental organizations, etc.). For example, the acceptable water limit (W_a) consists of a percentage of all available water resources that are allocated for agricultural production. The same goes for L_a, the percentage of arable land. Acceptable energy (E_a) represents a percentage of the energy allocated for agricultural sector and associated practices. Acceptable carbon limit (C_a) represents a maximum cap for emissions associated with agriculture and agriculture-related practices (water for agriculture, etc.), which could be influenced by national carbon emission reduction commitments and respective quota coming out of the agricultural sector. Acceptable financial limit (F_a)

represents a portion of the state budget associated with the scenario. EIMP and CIMP are less significant and could be more subjective as they look at energy consumption and carbon emissions in a global context, through transport of products.

2- Importance coefficient identification – Policy Input

Bringing together scientific knowhow on the one hand, and policy making on the other is critical: both contributions must be captured in the process of identifying sustainable strategies. The input of policy makers is needed after calculating different resource requirements for the scenarios. Their input consists of identifying the relative importance of reducing each of the resource requirements (water, energy, carbon, land, financial).

Stakeholders might assign an importance coefficient to each parameter, depending on what they view as most important to be reduced and in line with their policies and strategies. After that, the sustainability index of each of the proposed scenarios can be calculated. This index comprises the summation of the products of the "resource indices" with the assigned "importance coefficients".

A lower assessment parameter index indicates that parameter is farther from the maximum set limit which makes the scenario more favorable. Also, the lower the importance coefficient, the less important and sensitive the parameter. Thus, the scenario with the lowest score would be most sustainable, as defined by the decision maker.

$$\text{Scenario i: S.I.}_i = [WI_i (100\text{-}I_W) + LI_i (100\text{-}I_L) + EI_i (100\text{-}I_E) + CI_i (100\text{-}I_C) + FI_i (100\text{-}I_F) + EIMP\,I_i (100\text{-}I_{EIMP}) + CIMP\,I_i (100\text{-}I_{CIMP})]\, x100$$

$$I_W + I_L + I_E + I_C + I_F + I_{EIMP} + I_{CIMP} = 100$$

D. 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 addressed in this study are agricultural crops and do not include meat, dairy products, processed foods, and other food categories.
- The existing tool assesses the environmental impact of a scenario only through calculating its carbon emissions: no calculations are yet incorporated to quantify effects on water and soil quality.
- Current local characteristics information (figure 4) are based on estimations of locally collected data, and data that represent characteristics of similar environments. The ability to ensure locally

measured data (water requirements, local yields, energy requirements…) would provide more refined results.

- Relationships between system components are based on empirical, not process based data.

- The tool, at this stage, assumes linear relationships between systems that may not reflect reality.

- The current tool does not capture future projections of price inflation, 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). The scope of the framework is national, and interconnections among different frameworks, representing different countries, need to be further developed in order to create a global picture that could capture the comparative advantages of producing different products in specific locations. This would also help better assess 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 cost of products in market 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 separately assessed after, and then included in the financial cost. It is also assumed that exports are being sold at an average cost equal to the cost of import.

- Different risks are associated with created scenarios qualitatively assessed in this study. Further work could set a specific methodology to quantify these risks.

- Input from science and policy making is imperative to contribute to the process as defined by the tool structure (figure 4). A focus group including a mix of scientists and decision makers is recommended in order to develop acceptable limits and importance coefficients, while maintaining a high level of communication.

III. WEF NEXUS TOOL EVALUATION: OVERALL TOOL PERFORMANCE AND SENSITIVITY ANALYSIS

A. Overall performance

Governed by the presented methodology and tool structure, the user is able to create different scenario variations by changing self-sufficiencies of food products, type of agricultural practices (open versus protected agriculture, whenever applicable), sources of water, sources of energy, and countries of import. The table represents five scenarios which will be demonstrated and further discussed. The scenarios vary between full food self-sufficiency (%SS=100) in scenario 1, and full dependency in scenario 5 (%SS=0).

The different components of the scenarios are present in Table 1. The scenarios were created with the aid of WEF Nexus Tool 2.0$^{©}$.

Data from Qatar is used to demonstrate the tool. The data used consists mainly of the information characteristic to the study area (figure 4). The list of food products includes tomato, eggplant, lettuce, carrot, watermelon, cucumber, potato, and green onion. This list is chosen for demonstration purposes, as it also represents main elements in a Qatari diet, currently grown in varying levels of self-sufficiency. Preliminary assessment is done to evaluate the rationality of the results and assess the performance of the tool.

Figure 5 shows the tool results for the proposed scenarios:

Water and land are linearly affected by the change in percentages of self-sufficiencies and agricultural practice (figure 5). We can clearly see how water and land requirements linearly decrease as a result of the decrease in self-sufficiencies of products between scenario 1 and 5.

With regards to financial assessment, a similar relation exists, but it is not as obvious, 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 having the cost of imports, in almost all cases, 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 cost associated with the use of different energy or water sources across scenarios are not captured in this analysis.

The highest energy requirements are needed for scenario 2. Scenario 2 proposes full self-sufficiency with groundwater and desalination as sources of water. In comparing E_1 (energy for water) and E_2 (energy for food) values respectively, we can see that the total energy (E) is more influenced by E_1. When RO plant was introduced in scenario 2, E_1 showed a great increase in energy requirements. Even when self-sufficiency was reduced to half (scenario 3), the energy requirement still 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 producing the products locally, shows a trend that follows the decrease in self-sufficiency for scenarios 1 to 5.

Carbon emissions for scenarios varied according to the type of fuel used in each. While carbon emissions are mainly affected by the amount of energy consumed, the type of fuel is the major player. For example, the use of solar energy in scenario 3 to power RO plants 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 that is reflective of the linear relation that exists between it and the percentage self-sufficiency of food products.

E IMP, the energy consumed through transporting imported food products, increased 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 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, the carbon emissions due to energy consumed through transporting imported products, showed a similar increasing trend with decreasing self-sufficiency. According to the demonstrated scenarios and results (trends), the tool is preforming as expected.

B. Sensitivity analysis (relative sensitivity)

Further evaluation of the tool's performance is accomplished through sensitivity analysis of the different input parameters. There 3 types of inputs: food, water, and energy inputs (figure 6). The choice of % Self Sufficiency and % Open Agriculture for the different food products determines how much land (ha), water (m^3), financial cost ($), and energy in agriculture (E_2) are needed, as well as respective carbon (C_2) emitted. The choice of countries of import affects how much energy will be required through import (E IMP) and the respective carbon emitted (C IMP). After determining how much water will be 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 that would hence be 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 new output, O_b is output of base scenario, P is new parameter value, P_b is the base parameter value in base scenario.

In the following, Base Scenario I is presented in Table 2. In Assessment I-Food Input, the % self-sufficiency and % open agriculture will be changed for each of the food products. The main goal of this section is evaluating the tool with different sets of possible data.

- **Assessment I- Food Input**

Base Scenario I (Table 2)

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 7:

- First, the change in %SS_i has an effect on all measured output parameters.
- There is an inverse relationship between %SS_i and F_{IMP}, E_{IMP}, and C_{IMP}. That is pronounced through the negative relative sensitivity values that exist among them. When the self sufficiency of a chosen product increases, the total cost of imports, energy consumed through transporting imports, and carbon emitted as a result of the transport energy decrease.
- The relations that exist 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 sufficing water for scenarios (E_1), and carbon emissions relative to E_1 (C_1), have a similar trend for the different food products. Similarly, 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 could be produced in either open or protected agriculture in Qatar.
- According to figure 8, it is noted that the change in percentage of open agriculture (%OpAg.) has no effect over local and import financial costs (F_{Local} and F_{IMP}), energy consumed through transport of imports (E_{IMP}) and respective carbon emitted (C_{IMP}). Relative sensitivity is zero. This validates the lack of relation between this parameter and output according to the tool structure. Ideally, the cost of locally produced crops can vary depending on the type of agriculture. Further studies could be done in this regard 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 gave similar relative sensitivity results for all outputs, thus validating the performance of the tool in that regard.
- We also note, from figure 7 that the relative sensitivity of changing 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.

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- **Assessment II- Water Input**

In Assessment II, the source of water was changed *ceteris paribus*. (II-A: 100% RO Desalination, II-B: 100% MSF Desalination, II-C: 100% MED desalination, II-D: 100% Treated waste water).

Base Scenario II (Table 3)

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 (Figures 9 and 10). This scenario 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.

- **Assessment III- Energy Input**

Base Scenario III (Table 4)

The Base Scenario III is the same as Base Scenario II. The only thing changing here is the source of energy (the self-sufficiencies, type of agriculture, and water source (100% GW) remain the same). The reason only C_1 is changing is because gasoline 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 11).

The main building block for calculations in the tool is consumption values for the chosen food products (ton/year). Fifteen percent increase in tomatoes is not equal to a fifteen percent increase in eggplant (in 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 7). In Assessment I, 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. 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 the highest in terms of consumption for year 2010 (in tons), any change in the choice of producing them locally has the greatest impact on different requirements. Assessment 2 evaluations support the fact that change in the sources of water and the technologies used for the scenario effect the energy use and carbon emissions (Figures 9 and 10). Future improvements to the tool need to include the extra costs that come with adopting different technologies. Assessment 3 evaluations show how 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 itself is dynamic and would need further advancement.

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IV.   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 this section include scenarios using the same 8 food products used earlier. Following that, analysis regarding the potential of growing wheat, a staple cereal, will be performed.

Figure 12 depicts the situation in Qatar, based on the latest available data (2010). The combined self-sufficiency of the 8 food products is 15% (2010). Among the products listed, only tomatoes and cucumbers are produced in both open and protected agriculture conditions. All others are produced with open agriculture. Ground water is the main source of water for irrigation. Natural gas is the main source of energy. Imports are mainly secured from 15 countries. The results (figure 12) show the requirements needed for the actual 2010 scenario.

Due to the fact that the study is limited to 8 food products, comparing the scenario's requirements to maximum acceptable national limits is of limited value. Once a more comprehensive basket is analyzed, this step could be further discussed.

The presented eight food products are among the products currently being produced and are expected to have an increase their self-sufficiency. It would thus be useful to create hypothetical self-sufficiency increase scenarios for the products and assess the expected resource requirements. Then we could identify which of the resources is most critical, while adopting any decision concerning increasing food self-sufficiency.

Each of the eight food products has a different self-sufficiency value for year 2010. Graphs in figures 13 and 14 represent the percentage change in the required resources as a result of an increase in the self sufficiency of each of the products. Figure 13 shows how much more resources would be needed if the self-sufficiency of each of tomatoes, cucumbers, water melon, green onion, lettuce, potato, eggplant, and carrots was increased by an increment of 10% (i.e. if current self-sufficiency of tomatoes is 15%, in this scenario it is raised to 25%)

In the case of a 10% increment in the self-sufficiency of each of the products, for example:

- The overall self-sufficiency increase is 25%. It is significant to notice that a 25% increase in self-sufficiency of these products requires 82% more water, 153% more land, 82% more energy for sufficing water, and 97% more energy for local food production. 82% more carbon will be emitted as a result of energy consumed for sufficing 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%. The energy consumed and carbon emitted through transporting imported food products would decrease by 11%.

- As the percentage self-sufficiency increases and as expected, a linear trend in resource requirements is noticed as a result of the linearity of the tool relations (which is not necessarily reflective of reality).
- Land demand increases as the slope becomes steeper, and this is followed by increases in energy required and carbon emission for local food production; similarly for water, energy and carbon for water production. Based on the preliminary projections of the study sample in Qatar, possible conclusions follow.
  - 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 need to be created in order to choose the optimum spaces for producing the specific food products. Technologies for cultivation methods that reduce or minimize land requirements need to be investigated and considered (hydroponics, more products to be grown in green house environments…).

  - Energy requirements and carbon footprint for food production rank second after land. Investing in more efficient machinery for tillage, harvest, and transport should be considered. (Note: These recommendations are based on assumptions for tillage, harvest, transport and fertilizer production. When local data is collected for these items, more accurate conclusions can be derived). Gasoline was used as fuel for these practices. Investment in machinery that consumes less carbon emitting fuels could be considered as a way to mitigate the increase.

  - Water, energy for water, and respective carbon footprint
    The current scenario relies on groundwater for irrigation. With the current replenishment rates in Qatar, keeping this reliance on groundwater could lead to catastrophic consequences. Any plan of increasing food self-sufficiency should be supported with the items listed below.
      - Create a plan for investing in less water demanding technologies/new irrigation techniques
      - Rely on sources other than groundwater for securing water for food production. This could include specifying a portion of desalinated water for this purpose. If current capacities would not be able to hold the extra demand, investing in upgrade should be considered. Due to the direct relation between securing water, the energy consumed, and carbon emitted, low energy-low carbon emitting options need to be adopted.
      - Explore potential of different renewables to fuel the technologies needed for securing the water needed.

- Assess the financial costs of investing in these new technologies and increasing current capacities (not currently captured by tool).

- F-Local and F-IMP

  The local financial cost of food production is the least sensitive among the other resource requirements. Any anticipated increase in financial costs need to be properly integrated in 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, until it reached a peak in the early 1990's with 4MMTon/year (IndexMundi, 2014). That practice greatly consumed ground water resources, most of which being non-renewable. While developing a food security plan, wheat has a significant strategic importance for being among the staple cereals. According to UN Comtrade, around 400K tons of wheat were imported into Qatar in year 2010. Based on the previous analysis for base year 2010 for the 8 food products, while keeping all self-sufficiencies the same, the following analysis measures the percentage change in resource needs after introducing additional local production of 10% of the consumed wheat.

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

VII. CONCLUSIONS

Water, energy and food are highly interconnected and their interlinkages need to be reflected in the planning and decision-making landscapes that govern the management of these resources. Defining the local sustainability through input from involved stakeholders, as well as from the scientific and policy making arenas, is key for 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 which 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 the needed goals. Further work needs to be done in the direction of improving the existing functions within the framework, as well as building the ability to create scenarios that are energy or water focused. The use of the framework and tool would then depend on what critical questions the user needs to answer. Based on the Qatar case study, land is the requirement most sensitive to variations of food self-sufficiency scenarios. 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. Heavy 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.

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Tables and figures

Table 1: Components of five different scenarios

	Scenarios				
	1	**2**	**3**	**4**	**5**
% SS	100	100	50	25	0
%OP Ag.	100	100	50	0	NA
Water Source	100% GW	50%GW 50%RO	50%GW 50%RO	25%GW 50%MSF 25%RO	NA
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	NA
Countries of Import	status quo	status quo	status quo	status quo	status quo

Table 2: Base scenario food, water and energy inputs and output requirements (Assessment I)

INPUT							OUTPUT	
Food Products			Water Sources		Energy Sources		W (m3)	3.9E+0.7
							L (ha)	4947
							E1 (kJ)	1.7E+11
	%SS	% OP AG.		%		%	E2 (kJ)	4.3E+10
Tomatoes	30	85	Ground Water	100	Diesel	50	E (kJ)	2.1E+11
Eggplant	45	100			Natural Gas	50	C1 (ton CO2)	2.8E+07
Lettuce	17	100			Wind	0	C2 (ton CO2)	3038
Carrots	20	100			Solar Thermal	0	C (ton CO2)	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	EIMP (kJ)	1.1E+12
Green onion	20	100					CIMP(ton CO2)	6E+0.9

Table 3: Base scenario food, water and energy inputs and output requirements (Assessment II)

INPUT							OUTPUT	
Food Products			Water Sources		Energy Sources		W (m3)	3.9E+07
							L (ha)	4,947
							166,711,848,094	1.7E+11
	%SS	% OP AG.		%		%	E2 (kJ)	4.3E+10
Tomatoes	30	85			Diesel	100	E (kJ)	2.1E+11
Eggplant	45	100			Natural Gas	0	C1 (ton CO2)	2.8E+07
Lettuce	17	100			Wind	0	C2 (ton CO2)	3038
Carrots	20	100	Ground Water	100	Solar Thermal	0	C (ton CO2)	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	EIMP (kJ)	1.1E+12
Green onion	20	100					CIMP(ton CO2)	6E+0.9

Table 4: List of energy sources for scenarios (Assessment III)

Scenario	Energy Source
Base III	Diesel
III-A	Natural Gas
III-B	Wind
III-C	Solar Thermal
III-D	Geothermal
III-E	Nuclear
III-F	Biomass
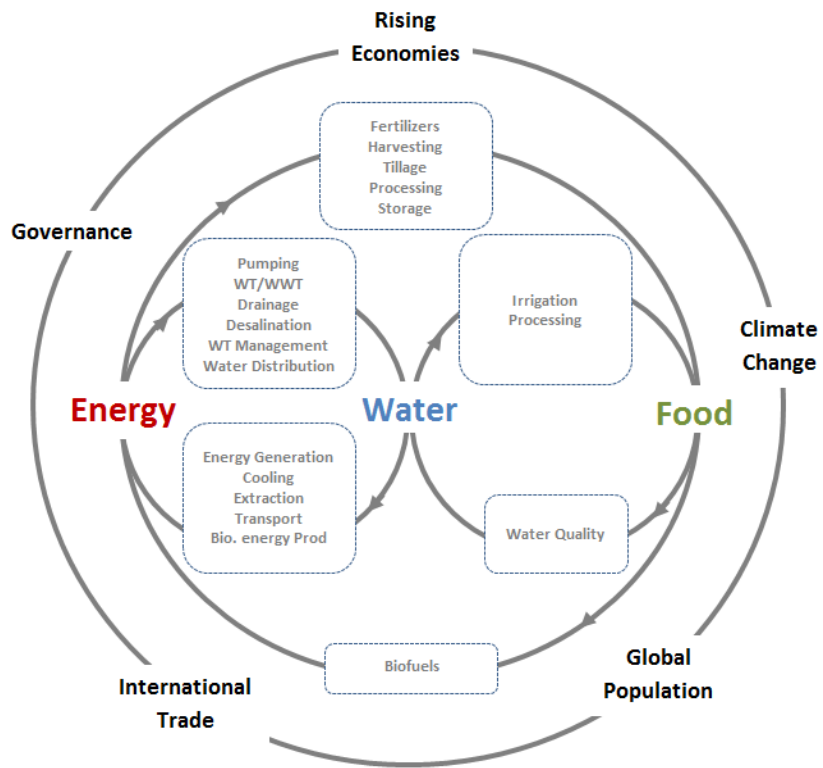
Figure.1: Schematic showing the water-energy-food nexus with effecting parameters

(Rabi H. Mohtar, Bassel Daher, 2012)
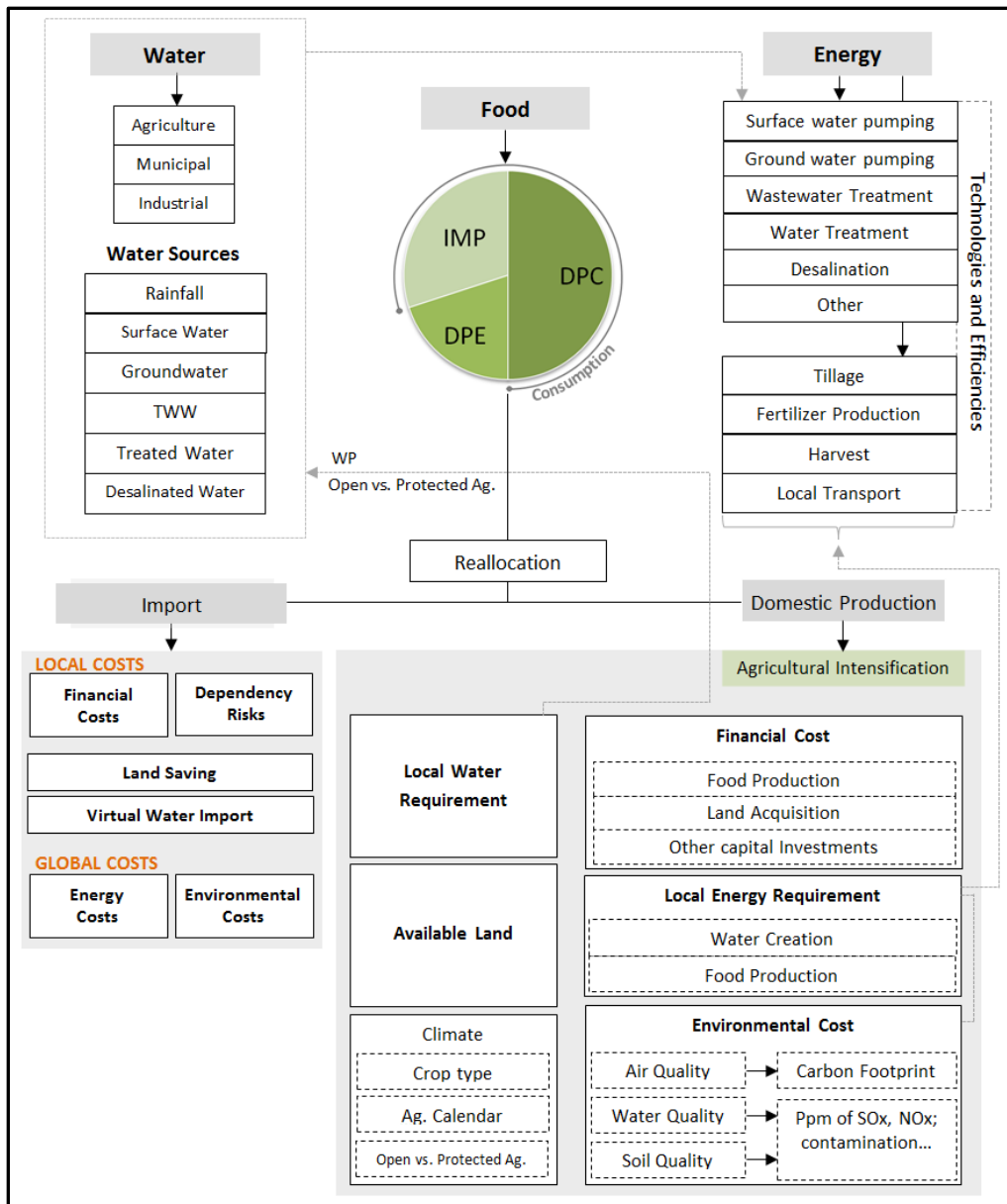
Figure 2: Water, energy, and food conceptual scenario-based framework
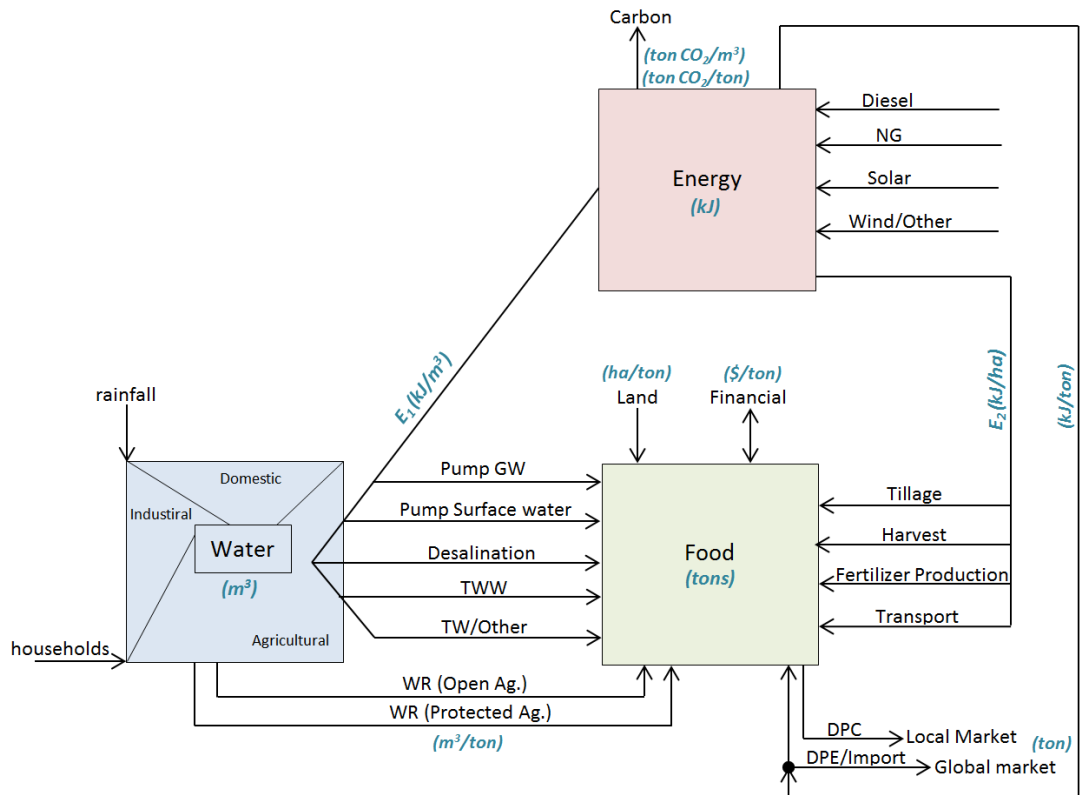
Figure 3: Block diagram demonstrating the water, energy, and food nexus framework
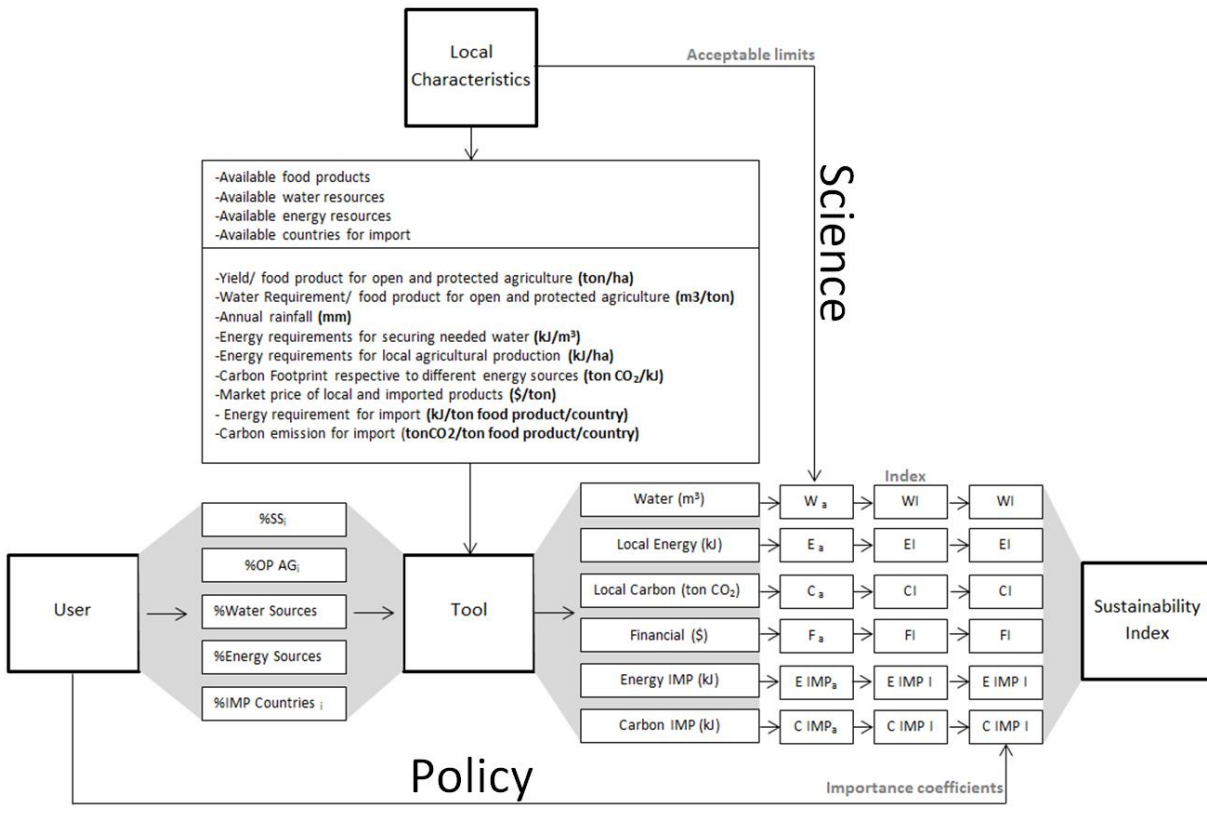
Figure 4: Tool structure and the calculating sustainability index
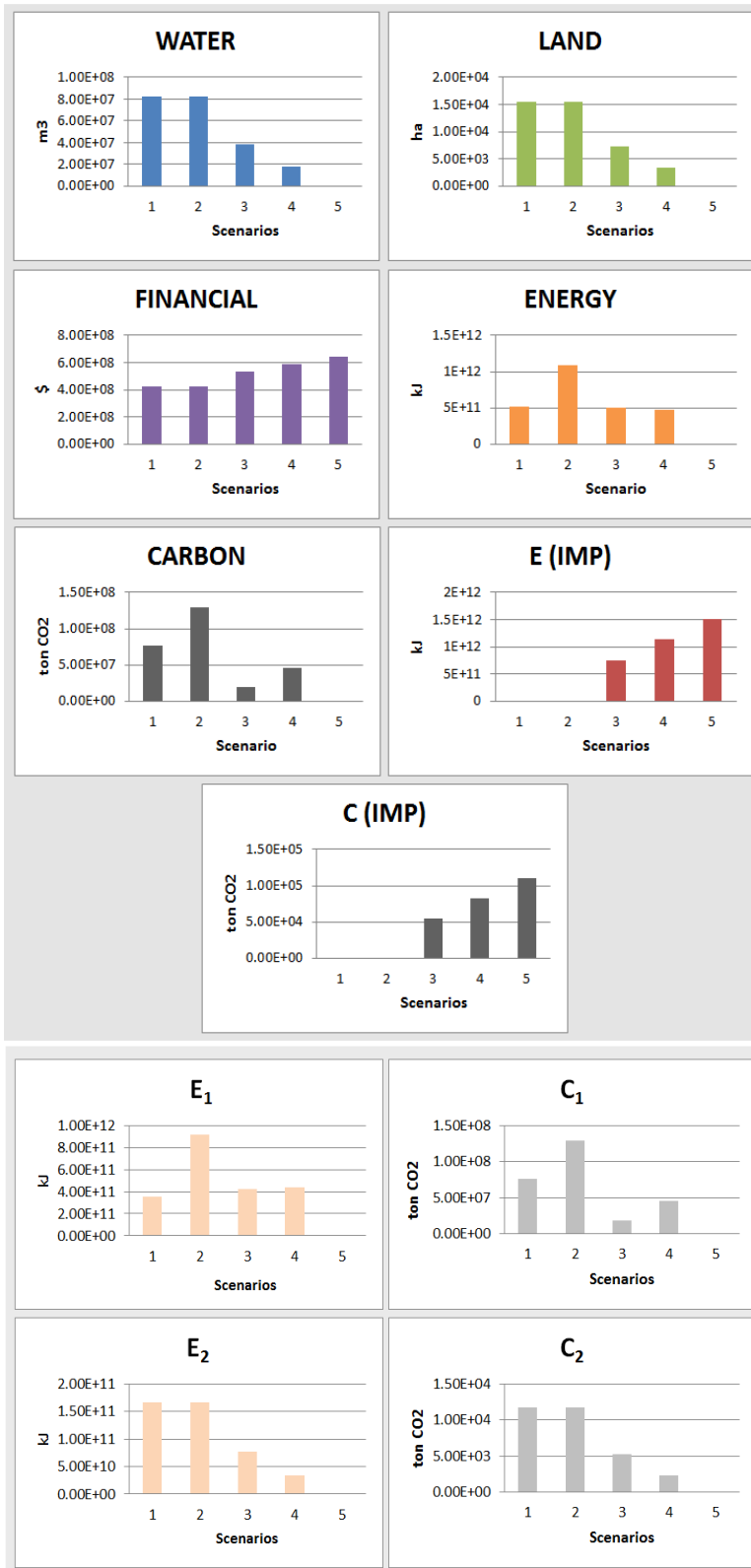
Figure 5: Tool output for the five input scenarios
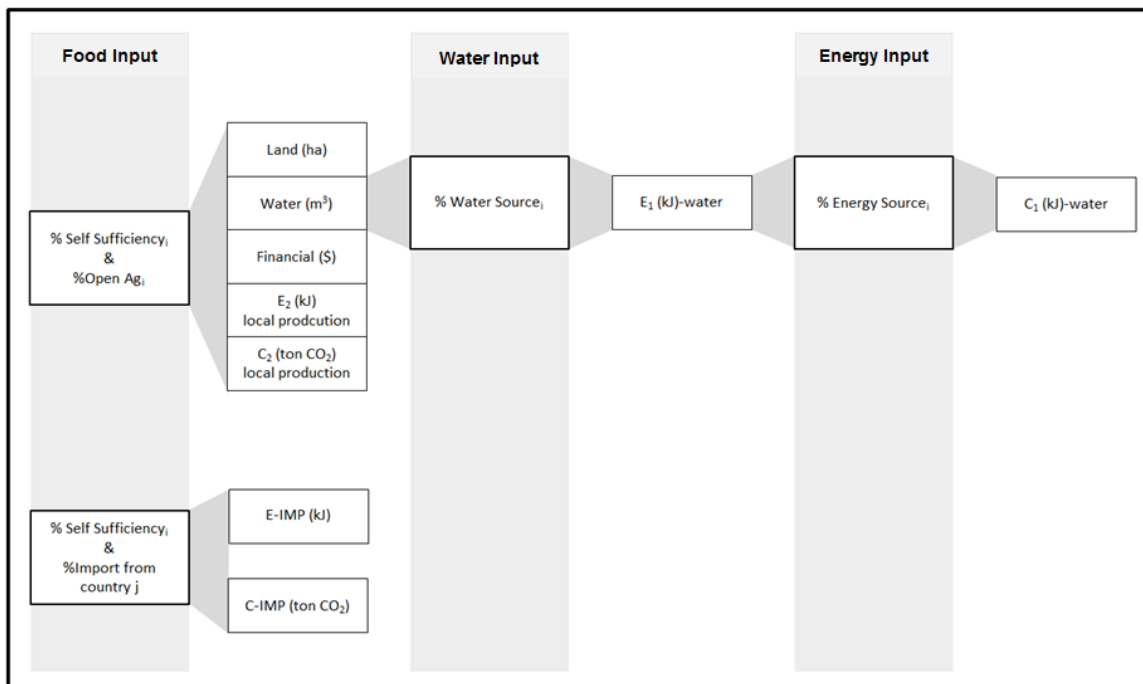
Figure 6: Food, water, and energy input parameters and respective output
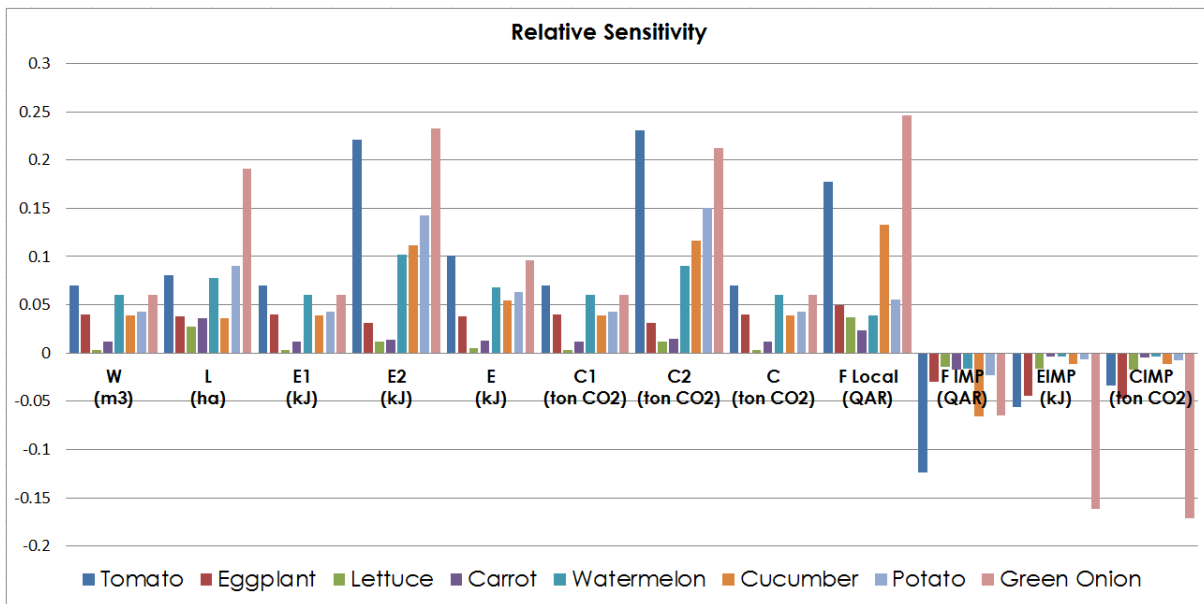
Figure 7: Relative sensitivity of 15% change in self-sufficiencies of the different food products on output
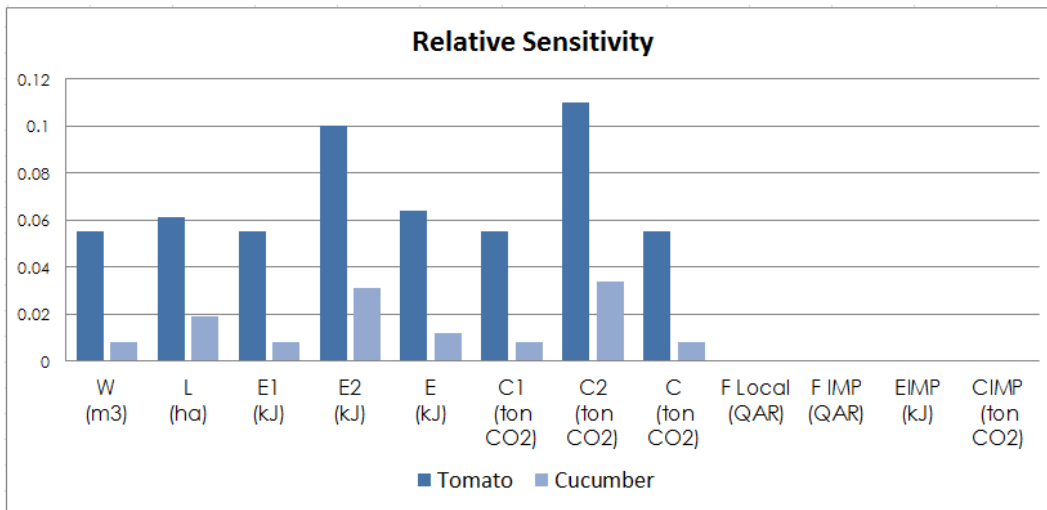
Figure 8: Relative sensitivity of the % of Open Agriculture for tomato and cucumber
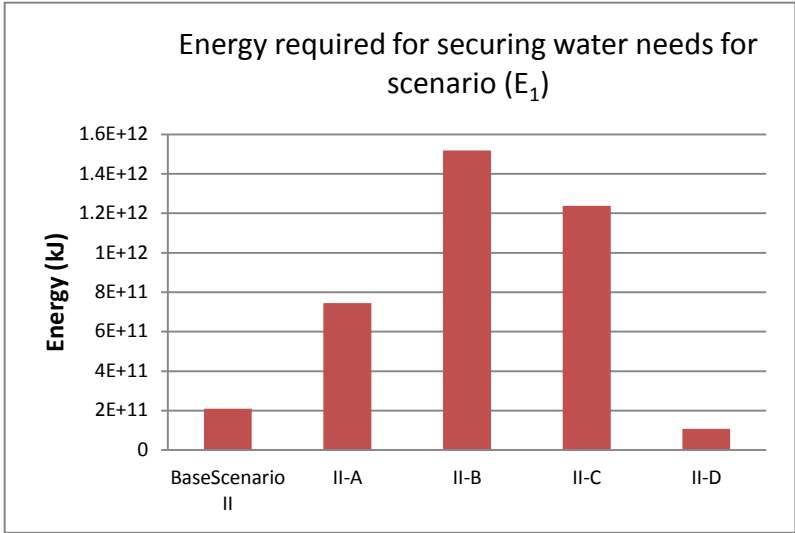
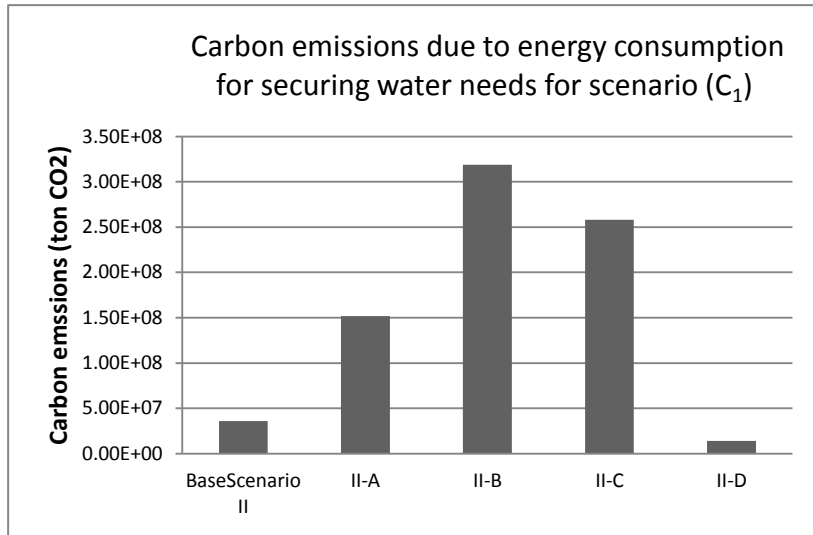Figure 9: Energy requirement E1 for Assessment 2 scenarios

Figure 10: Carbon emissions C1 for assessment 2 scenarios respective energy consumed for securing needed water for the scenarios
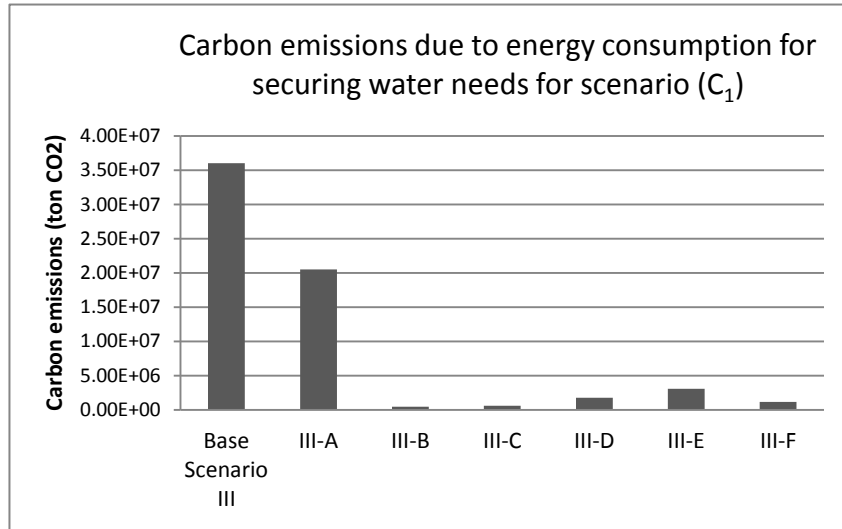
Figure 11: Carbon emissions C1 for assessment 3 scenarios respective energy consumed for securing needed water for the scenarios
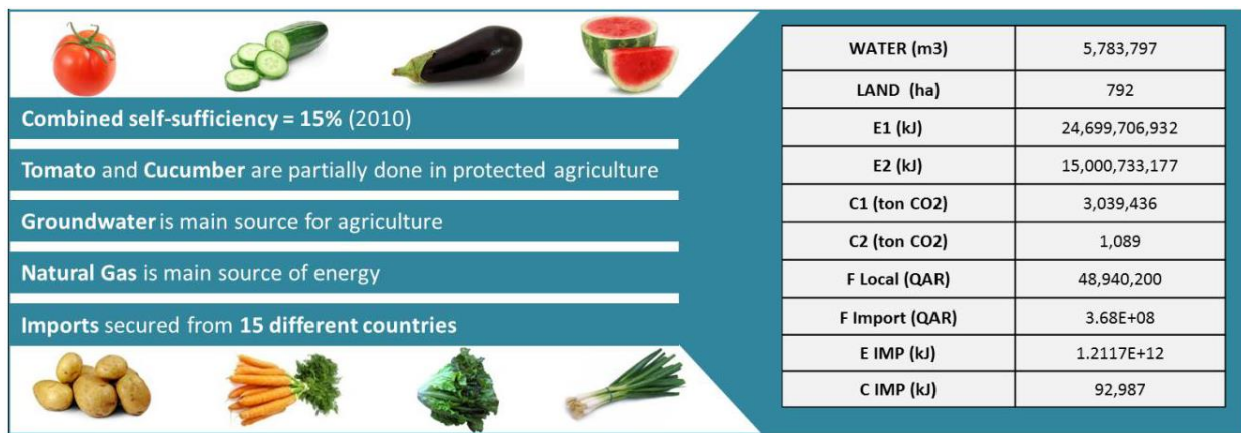
WATER (m3)	5,783,797
LAND (ha)	792
E1 (kJ)	24,699,706,932
E2 (kJ)	15,000,733,177
C1 (ton CO2)	3,039,436
C2 (ton CO2)	1,089
F Local (QAR)	48,940,200
F Import (QAR)	3.68E+08
E IMP (kJ)	1.2117E+12
C IMP (kJ)	92,987

Combined self-sufficiency = 15% (2010)

Tomato and Cucumber are partially done in protected agriculture

Groundwater is main source for agriculture

Natural Gas is main source of energy

Imports secured from 15 different countries

Figure 12: Resource requirement for a 2010 scenario (input data from QNFSP)
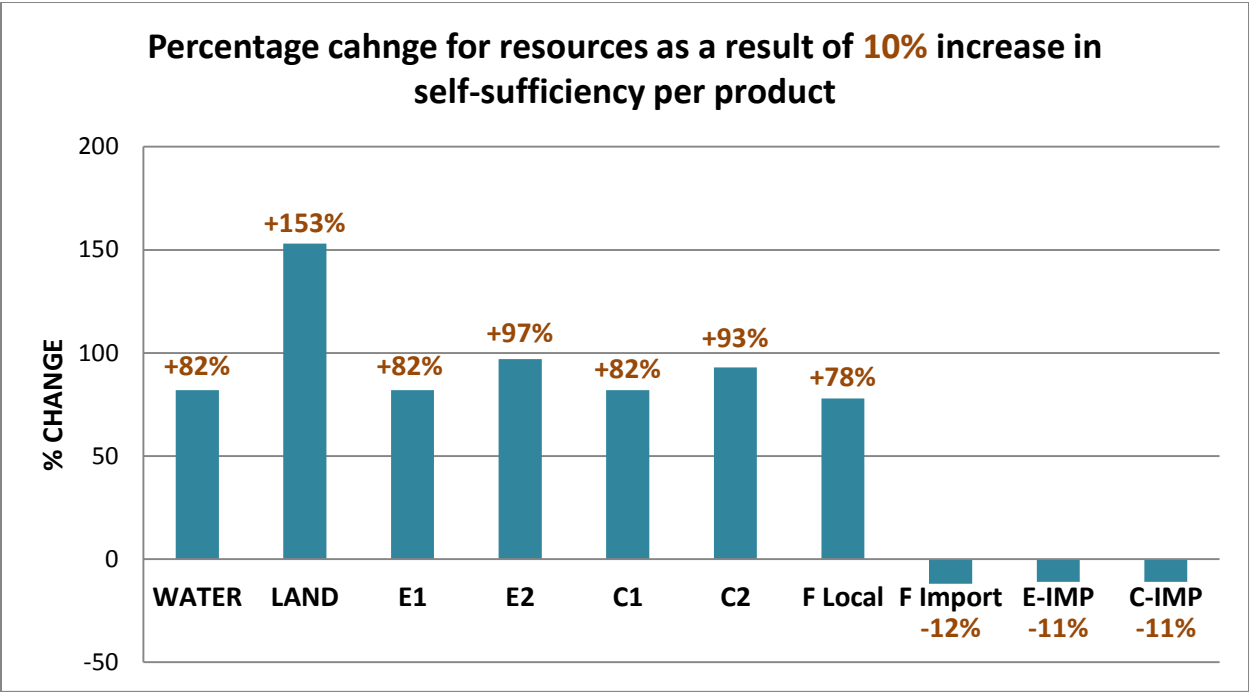
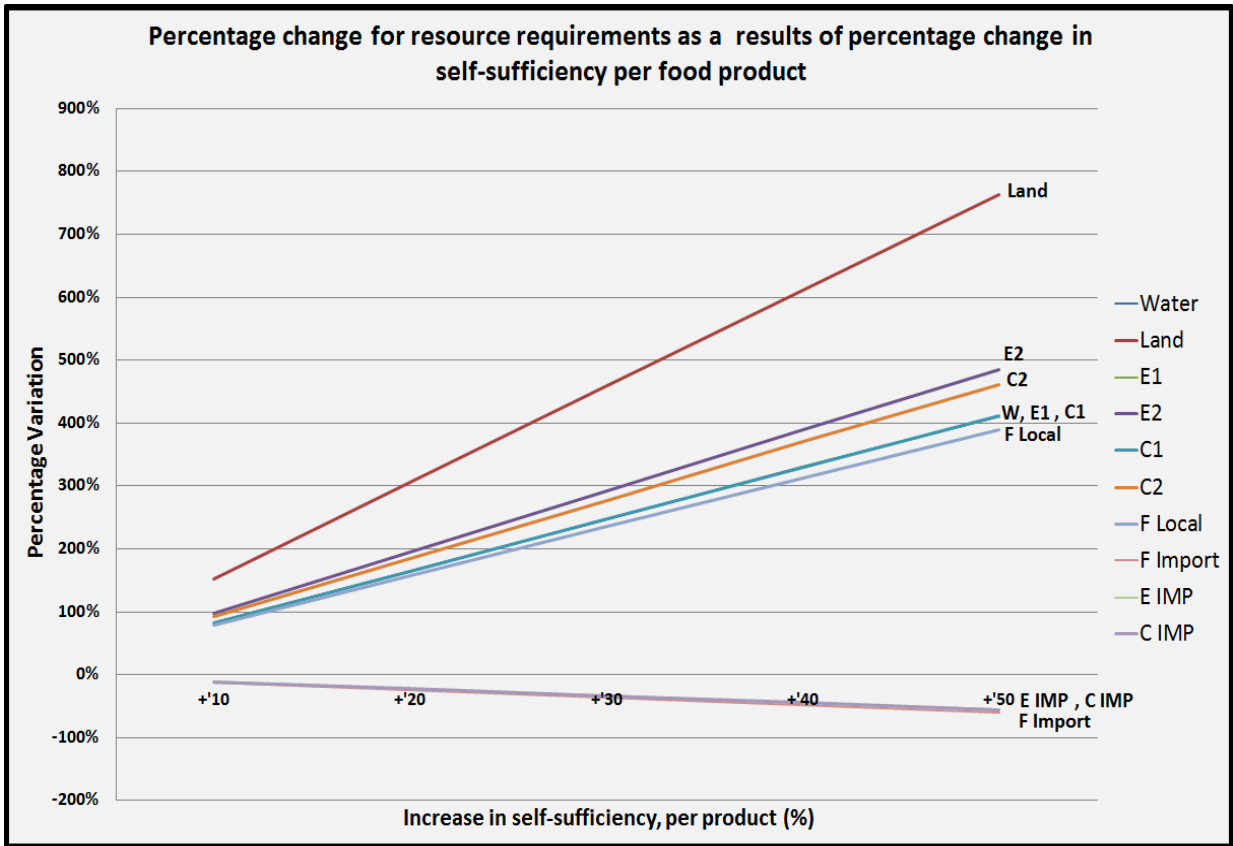Figure 13: Percentage change in the resource requirements as a result of 10% increment in self-sufficiency

Figure 14: Percentage change of resource requirements as a result of percentage change in self-sufficiency per food product
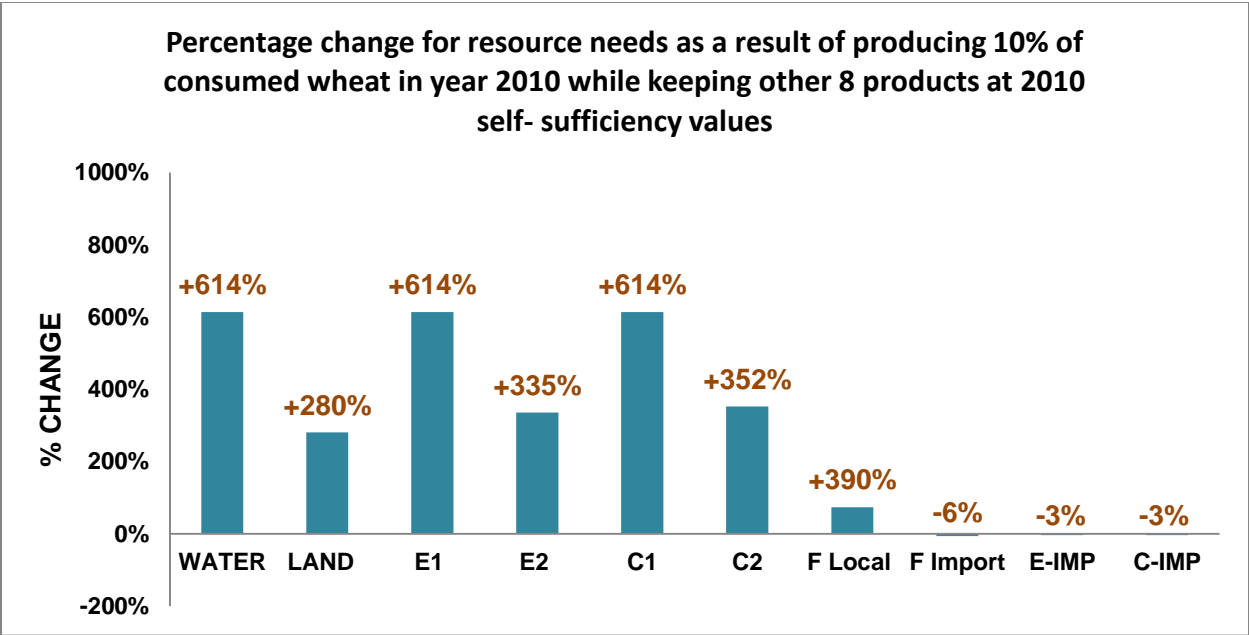
Figure 15: Percentage change in resource needs as a result of producing 10% of consumed wheat in year 2010