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Development of a life cycle assessment tool for the assessment of food production systems within the energy, water and food nexus

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ABSTRACT

As the demand for services and products continues to increase in light of rapid population growth, the question of energy, water and food (EWF) security is of increasing importance. The systems representing the three resources are intrinsically connected and, as such, there is a need to develop assessment tools that consider their interdependences. Specifically when evaluating the environmental performance of a food production system, it is necessary to understand its life cycle. The objective of this paper is to introduce an integrated energy, water and food life cycle assessment tool that integrates EWF resources in one robust model and at an appropriate resolution. The nexus modelling tool developed is capable of providing an environmental assessment for food production systems utilising a holistic systems approach as described by a series of subsystems that constitute each of the EWF resources. A case study set in Qatar and characterised by an agriculture sub-system, which includes the production and application of fertilisers and the raising of livestock, a water sub-system represented by mechanical and thermal desalination processes and an energy sub-system, which includes fossil fuel in the form of combined cycle natural gas based energy production and solar renewable energy is used to illustrate the model function. For the nexus system analysed it is demonstrated that the food system is the largest contributor to global warming. The GWP can be reduced by up to 30% through the utilisation of solar energy to substitute fossil fuels, which, however, comes with a significant requirement for land investment.

Keywords: Energy, water and food; Resource efficiency

1. Introduction

Increased human activity during the period following the year 1950, known as the “great acceleration”, is considered to have inflicted the most damage on the environment. Population doubled from 3 billion to 6 billion, economic activity increased 15-fold, petroleum consumption increased by a factor of 3.5, motor vehicles increased from 40 million to 700 million by 1996 and over 3 billion people now reside in urban settings (Steffen et al., 2011). The effects of these activities led to significant degradation in the sub-systems that constitute the Earth’s marine, terrestrial and atmospheric ecosystems. Energy demand is projected to increase by 37% by 2040 with Africa, Middle East and Latin America expected to represent approximately 60% of the global total (IEA, 2014a). At present, energy use is by far the largest source of emissions contributing 69% of global anthropogenic greenhouse gases emissions. Smaller shares correspond to agriculture (11%), producing mainly CH_4 and N_2O from domestic livestock and rice cultivation, and to industrial processes not related to

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energy (6%), producing mainly fluorinated gases and N_2O; with smaller contributions from numerous other sources (14% combined total) (EC-JRC/PBL, 2011). In terms of energy demand, developed countries have witnessed stabilised CO_2 emissions in the last few years whilst the Middle East and China have recorded the largest increases in CO_2 emissions (IEA, 2014b). Furthermore, the world's population is appropriating 54% of the accessible fresh water reserves which is expected to increase further with climate change and population growth. It is estimated that by 2025 there will be 1.8 billion people who will be living in areas of absolute water scarcity and two thirds of the world population could be under conditions of water stress (UN-Water, 2007). Whilst agriculture remains the largest consumer of fresh water with a 70% share of water utilisation, widespread food insecurity remains prevalent in the world today with hunger present in one out of every seventh person (UN-Water, 2015; WEF, 2014; Ericksen, 2008). The provision of food as a basic human right forms the foundation of food security as defined by the World Food Summit of 1996, which states that food security exists when "all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life" (FAO, 1996). Projections show that feeding the world population in 2050, expected to be at 9 billion, would require a 70% increase in agriculture and production in developing countries (FAO, 2009). This would require a significant input of energy, water and mineral fertilisers. Today, agriculture already contributes well over 10% of global GHG emissions (Brentrup and Pallière, 2008). In addition, there are manufacturing activities that are of sole benefit to the agricultural sector which need to be considered as part of the global agricultural system. For instance, consider the production of fertiliser, for which the production of nitrogen fertiliser alone is equivalent to 0.8% of global GHG emissions (Brentrup and Pallière, 2008). The role of livestock in climate change is of specific concern. This is because, livestock can contribute both directly and in-directly to climate change through the emissions of greenhouse gases (CO_2, CH_4 and N_2O). In fact, global CH_4 emissions are estimated at 2.2 billion tonnes of CO_2 eq. which account 80% of agricultural CH_4 and 35% of the total anthropogenic methane emissions. Furthermore, emissions of N_2O from the livestock sector represent 75% of total agricultural N_2O emissions (FAO, 2015).

Evidently, energy, water and food (EWF) systems are rapidly growing in demand, have different regional availability and have strong interdependences amongst themselves and both the human and natural environments (Bazilian et al., 2011). Furthermore, stressors on the EWF systems in the form of global trends consisting of population growth, climate change and urbanisation will further degrade their capacity to sustain global growth. In fact, much of the world's future challenges and uncertainty revolve around energy, water and food (WEF, 2015). As such, it is essential to refine the discussion on sustainability, resource consumption and security to one that alludes to the intricate interdependences between EWF systems. This will ensure that resource consumption and the impact on the natural environment are accurately accounted for and strategies for conservation can be developed (Bazilian et al., 2011; Hellegers et al., 2008; Harris, 2002).

With regard to evaluating interdependences between resources, the vast majority of previous work conducted considers the relationship between two resources, most notably energy and water. For instance, Malik (2002) discussed the energy and water nexus using the Indian experience at household level and suggested ways in which the gap between the two can be bridged. Lofman et al. (2002) provided a comprehensive review of the energy and water situation in the State of California and provided a series of policies that address the long term uncertainties within the energy and water nexus for the State. More recently, Siddiqi and Anadon (2011) reviewed the energy and water sectoral characteristics for the Middle East. They concluded that the nexus is highly skewed indicating that whilst energy production systems are weakly dependent on fresh water, the provision of fresh water (abstraction, production, distribution) is highly dependent on energy, a relationship similar to that observed by Lofman et al. (2002) in California. In many cases the focus of integrated assessment of the energy and water systems is on the need for cooling water in energy production, as electric power plants account for approximately half the global industrial water withdrawal (Davies et al., 2013).

In light of the growing concerns for food security, efforts have been made to expand the nexus boundaries to one that alludes to the relationship between energy, water and food resources. Bizikova et al. (2013) consider EWF resources in terms of their utilisation, accessibility and availability characteristics combining human and natural systems, all within an enabling governance structure. In the nexus framework developed by Hoff (2011) water plays a central role because it is a non-substitutable commodity. The WEF report (WEF, 2011) presented a nexus framework driven by risk to better understand the relationship between environmental pressures, resource security and economic disparity. This particular framework highlights the importance of considering the social and economic and dimensions of development in relation to the EWF system. It emphasises that failure to achieve security across all three EWF sectors will result in social instability and economic decay. Bazilian et al. (2011) suggested areas which would benefit from adopting a EWF nexus approach such as; energy access and deforestation, biofuels, irrigation and food security, hydropower and the provision of water through desalination. More recently, Bazilian et al. (2013) applied the energy, water and food nexus to algal systems with the objective of developing a framework to be used as a precedent for further analysis in this area.

In a case study, Wong (2010) applied the EWF concept to better understand China's resource challenges. In his review, it was concluded that the path forward with respect to energy production is the use of renewable energy not only because of the greenhouse gas savings, but because it uses less water. Improving water use efficiency through the reduction of leakages and the incorporation of innovative technologies such as drip irrigation is paramount to reducing water consumption. Wong (2010) highlights the resource burden associated with the raising of livestock. As such, the reduction in meat consumption is considered as one way to encourage the responsible utilisation of resources, a precursor to a sustainable society and upholding environmental integrity. This is because the raising of livestock releases significant amounts of methane, carbon dioxide and other greenhouse gases. In addition they are the largest consumer of water in the agriculture sector requiring up to 15,000 litres of water to create one kilogramme of boneless edible beef.

With respect to using a nexus based quantitative framework in order to address a policy question, the integrated climate, land, energy and water framework is the most advanced integrated resource model available (IAEA,

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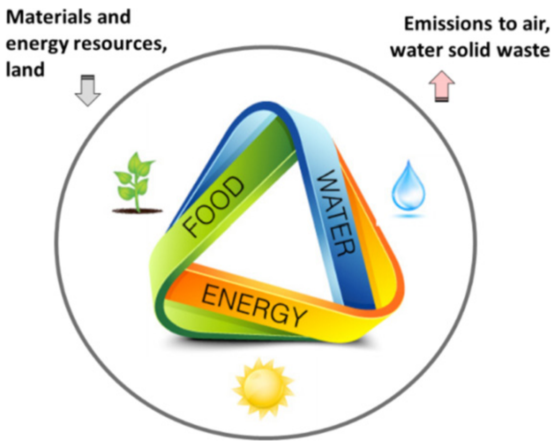

Fig. 1 – The energy, water and food nexus.
***Source:* Modified from Aquate (2015).**

2009). The framework is used to study the inter-relationship between climate, energy, water and land-use systems for the case of Mauritius. The model developed adopts an energy perspective to answer a particular policy question; "should sugar cane be processed into ethanol instead of sugar". To answer the question, a systems approach was adopted to develop a series of individual mass and energy based models for energy, water and land use to quantify; resource, economic and environmental implications (GHG emissions) for different scenarios under the same policy question.

Challenges related to the EWF nexus differ from country to country. Population growth and climate change represent the largest threats to the availability of the EWF resources (WBCSD, 2014). The ability to absorb these challenges depends on the vulnerability/resilience of supporting systems in addition to the economic capacity to mobilise alternative solutions. The effects of unsustainable resource consumption have already become obvious in various regions around the world, one such recent example is in California, where extreme droughts resulted in declaring a state of emergency for summer 2015.

Clearly EWF resources have intricate relationships which depend heavily on the geographical area of study. Assessment tools are required to adequately quantify the relationship between energy, water, food and the environment in order to identify and evaluate the trade-offs and synergies that would need to be considered as human economies continue to grow. At present there is no universally recognised methodology for nexus analysis which brings together both quantitative analysis and qualitative reasoning in relation to the environmental impact of the provision of a product or a service. The objective of this paper is to present the details and function of the EWF environmental assessment tool developed by the authors through the illustration of a specific case study centred around the energy, food and water nexus in Qatar.

Qatar is an affluent and arid country that suffers from a severe lack of natural water resources. Given that it is a small country, home to approximately two million people, it possesses a disproportionate distribution of natural resources. This characteristic will affect Qatar's ability to become fully self-sufficient as with any nation, resulting in a degree of dependence on global trade to satisfy domestic requirements. (See Fig. 1.)

Qatar's situation is particularly interesting; this is because whilst it has an abundance of energy reserves, it has a severe shortage of fresh water and arable land. It is also situated in a volatile region with extreme security risks and is a part of a global community that is vulnerable to the effects of climate change which will inevitably exacerbate its natural stresses. Annual freshwater extraction from aquifers is four times the rate of natural recharge of 50 mm^3/y. The depletion is driven by agriculture which represents only 1.6% of the total land area of Qatar, and provides for approximately 8%–10% of domestic food consumption and contributing 0.1% to the domestic GDP (QNFSP, 2013; Alpen Capital, 2011). The freshwater extraction is unfortunately leading to the greater salination of aquifer water and, to avoid this, fossil fuel powered desalination is used to provide more than 99% of Qatar's water demand (up to 539 mm^3/y). (See Fig. 2.) Q3

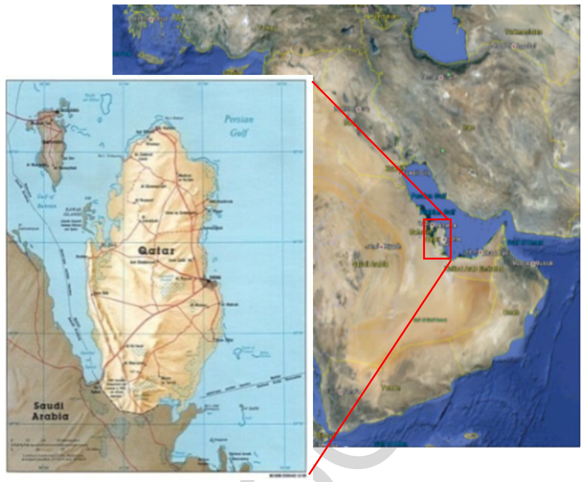

Fig. 2 – Location map of Qatar.
***Source:* Google Earth and the Atlas of the Middle East, 1993.**

In 2012 Qatar's electricity generating capacity reached 9,000 MW and is expected to rise with the predicted population growth. The total arable land in the countries representing the Gulf Cooperation Council is approximately 8% of the total land area and as a result imports represent approximately 90% of Qatar's food requirement (Alpen Capital, 2011). Furthermore, the total food imports will have to increase in order to accommodate the increasing population estimated at 14.3% per year. The case study presented here considers an increase in Qatar's domestic food production to 40% of the domestic demand by weight using a given crop profile by the year 2025.

2. Methodology

The EWF nexus tool utilises LCA to translate system outputs into environmental assessment scores. LCA is a methodological framework which involves the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product, process or system throughout its entire life. The objective of which is to understand and evaluate the magnitude and significance of the potential environmental impacts of a product system. The four main stages of LCA according to ISO 14040 are: the Goal and Scope definition; the Life Cycle Inventory analysis (LCI); the Impact Assessment (LCIA); and the Interpretation of the results. The Goal and Scope definition states the aim of an intended LCA study, the system boundary, the functional unit and the resolution (level of detail) in relation to this aim. The Life Cycle Inventory analysis is the phase which quantifies the input/output relationships and to prepare an

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inventory of input/output data for all component processes involved in the life cycle of the system under study. In this regard, MFA is essentially a means to build the inventory. With respect to LCIA, this paper employed the CML 2001 baseline impact categories (e.g. global warming, acidification, and human toxicity, etc.), category indicators and characterisation methods (Guinée et al., 2002). Additionally, in order to address the potential impacts of aquatic ecotoxicity introduced by brine disposal from desalination plants, an integrated aquatic ecotoxicity potential indicator for brine is implemented. The impact categories considered in this paper are listed in Table 1 together with a short description for clarity.

The LCI methodological framework for the EWF system is developed and used to evaluate the performance of different delivery pathways for a given functional unit. It is necessary that the principles that form the basis of the methodology are evident throughout the model development (Korre et al., 2010):

- Transparency: To show precisely how life cycle impacts are calculated and the extent to which the inputs/outputs of any unit process have been quantified.
- Comprehensiveness: To identify all of the inputs/outputs that may give rise to significant environmental impacts.
- Consistency of methodology: To present models and assumptions, so as to allow for valid comparisons between technological or operations options for each unit process.

The integrated assessment methodology developed by the authors can be used to assess a range of different product systems utilising EWF resources. The tool developed utilises well-established methodologies such as whole systems, LCA and material flow analysis (MFA) methodologies. The nexus assessment allows the product system under examination to be considered as part of the wider environment and in the context of high level national priorities. Furthermore, the output of the EWF nexus model can reflect the unsustainable nature of the product system in question and identify bottle necks, also known as areas of intervention within the unit processes.

The energy, water and food systems together form the product system, each represented by sub-systems, and described by individual unit processes. With emphasis on the inter-linkages between EWF resources, the tool developed allows to quantify material flows, natural resource and energy consumption at component unit process level. Each of the EWF nexus elements is described by a set of sub-system LCI models. Essentially, every sub-system model is designed using LCA principles using the appropriate reference unit (energy, water, food product respectively) and comprising the relevant unit processes and inventory. Intermediate products, which can be reused within a product sub-system or the nexus, remain within the overall system boundary. On the other hand, emissions beyond the system boundary are allocated and characterised using the CML 2001 baseline impact categories. The main features of the EWF nexus tool developed are as follows:

- Integrated modelling is used to track energy and non-energy related GHG emissions, solid wastes, toxic liquid emissions, air pollutants and the consumption of natural resources.
- The holistic approach ensures that a spectrum of environmental impacts and relevant trade-offs can be explored. For instance evaluating whether a reduction in GHG emissions will result in increased emissions and impact in other life cycle categories.
- The design of LCI models at component unit processes level allows for process parameters to be adjusted according to the examined scenario.
- The nested and modular structure implemented allows the flexible update of the LCI models and the possibility to examine multiple scenarios.
- The environmental performance of different scenarios can be examined in terms of specific emission, resource consumption or life cycle impact category score.
- It is possible to identify the substances and unit process that contribute significant burden, with the aim to mitigate the impact through process reconfiguration or technology intervention.

The tool integrates the utilisation of EWF resources in a single resource model and estimates the performance of a given system configuration delivering a product or a service on atmospheric, terrestrial and marine ecosystems. The modular nature of the tool through subsystems enables the accurate representation of complex systems and allows the identification of system inefficiencies (Al-Ansari et al., 2014). This approach makes sure that the models designed can be used to represent technical, spatial and temporal differences that exist between different systems and unit operation effects can be accounted for by modifying appropriate parameters of the component unit processes.

The tool is set apart from earlier approaches in that it considers the inter-linkages between all three EWF resources and that the process models developed offer adequate resolution, avoiding the use of generic data bases where possible. Furthermore, setting up the models and inter-linkages at unit process level offers significant advantages over gate-to-gate data gathering methods, which generally imply that component systems are simplified to a simple black box with constants and where linear coefficients have been used to assign inputs and outputs. For instance, the electricity generation data of mainstream LCA software and databases place more emphasis to the system boundaries (gate-to-gate data) rather than prioritising the detail in unit process representation. This results in lower accuracy for emissions and estimated impacts, as well as limitations in representing the technical and geographical characteristics of the scenario considered.

The model presented allows the user to consider the actual variability of process parameters and operating conditions. Furthermore, the modelling approach enables to identify and quantify the inter-relationships between energy, water and food as a function of the type of technology and the region in which it is used. This allows for specific environmental pressures to be identified and tailored solutions to be engineered. The EWF nexus tool developed is indeed able to answer key questions regarding the utilisation of resources and the impact a particular policy may have on the environment. This paper will consider the fundamental question concerning the environmental burden of the provision of food in water-scarce countries. As such, with food as the focus of the model, Qatar is chosen as a test site. Finally, it is should be noted that whilst the focus of this paper is food, the EWF nexus tool can easily be re-arranged to consider energy or water as the focus of the analysis.

3. System definition and life cycle inventory models developed

The EWF nexus model consists of a series of sub-system LCI models developed to quantify material flows, natural

Table 1 – Description of main LCA impact categories considered.

Impact category	Relevant LCA data	Characterisation factor
Global warming		
Refers to the impact of anthropogenic emissions which enhance the radiative forcing of the atmosphere, cause the temperature of the earth's surface to rise.	Carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), chlorofluorocarbons (CFCs), hydro chlorofluorocarbons (HCFCs), methyl bromide (CH_3Br)	Global warming potential: converts LCI data to carbon dioxide (CO_2) equivalents.
Acidification		
Refers to the acidifying pollutants' potential impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials.	Sulphur oxides (SOx), nitrogen oxides (NOx), hydrochloric acid (HCl), hydrofluoric acid (HF), ammonia (NH_3)	Acidification Potential: Converts LCI data to Hydrogen (H^+) ion equivalents.
Human toxicity		
Covers the potential impacts on human health of toxic substances present in the environment.	Total releases to air, water and soil.	LC50: converts LC50 data to equivalents.
Depletion of abiotic resources		
Refers to the depletion of natural resources (including energy resources) which are regarded as non-living.	Quantity of minerals and fossil fuels used.	Resource depletion potential: converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve.
Aquatic eco-toxic potential		
Refers to the potential impacts of toxic substances on aquatic ecosystems.	Toxic chemicals of brine disposal from desalination plants.	Factors are calculated for groups of chemicals within the brine effluent.
Land footprint		
Refers to land area occupied from agriculture and process facilities.	Area of farming and solar power facilities are considered.	

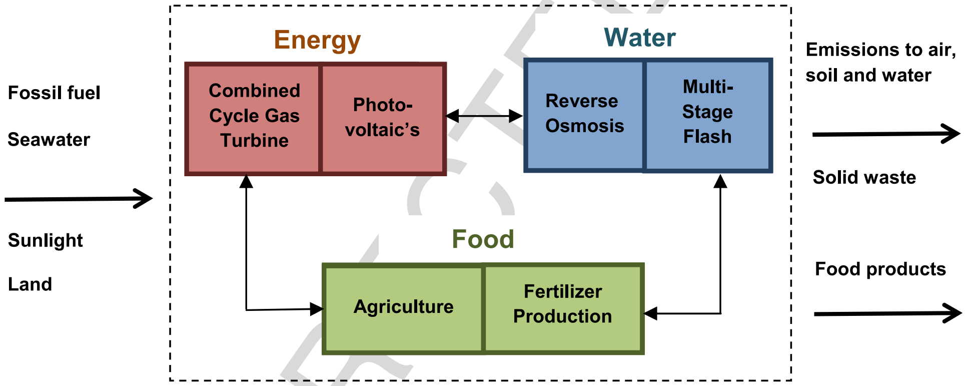

Fig. 3 – Schematic of EWF nexus and sub-systems.

resource and energy consumption at component unit process level. The LCI models are built using a combination of mass balance models, literature emission factors and engineering calculations, which are validated using published literature and industry data. The flexible structure of the LCI database, provided through modularisation, enables the practitioner to choose component unit processes so that different technological options can be considered without the need for re-design or loss of information. The nexus modelling system presented here has adopted a food perspective with the objective of evaluating the impact when raising domestic production.

The relationships between energy, water and food subsystems considered are outlined in Fig. 3 depicting the main inputs, outputs and sub-system interactions. The transfer of products between sub-systems represents: (1) the energy required for the production of water and the water requirement in the conversion of energy to power; (2) the water requirement for irrigation and the production of fertiliser, the physical representation of virtual water in food products, (3) the energy required to power facilities within the food system and the opportunity to utilise food products or solid wastes from within the food nexus element for energy generation.

The analysis presented in this study evaluates three possible scenarios which can deliver the same food production profile (this is the functional unit of the EWF nexus), designed to deliver a hypothetical degree of self-sufficiency for Qatar. The crop profile involves a hypothetical scenario involving the production of 40% of Qatar's domestic consumption demand by weight and is focused on perishable food items because they represent the highest food security risk. The high risk is assigned because these food products they are most likely to lose quality/freshness in the case of a severe disruption or shock in trade routes. An additional reason for the choice is because perishable foods require less water to produce, which is desirable for local production in water-scarce environments. Finally, as this would be a newly designed fresh food production process, best in class production practices can be selected, ensuring high quality and nutritional value as a result of shorter storage times and supply chains. The distribution of the crop profile by volume: open field agriculture; i.e. onions and potatoes (20%), protected agriculture, i.e. tomatoes and cucumbers (20%), fruits, i.e. dates and citrus (20%) and livestock products (40%). Legumes, fodder and cereals are omitted from the crop profile as they are considered unsuitable for growth in arid climates such as Qatar due

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Table 2 – Scenarios used to evaluate the food production profile.

Baseline scenario	PV integration for the water system	PV integration for the water and food system
CCGT is used to power all water and food production requirements.	Solar PV is used to power RO desalination.	Solar PV is used to power RO desalination and production of fertiliser.

to their respective large water requirements, especially using expensive desalinated water.

The livestock under management include broilers, dairy, beef, sheep and camels. This production and application of fertilisers and the raising of livestock represent the sub-systems of the food nexus element. The water sub-system includes Multi-Stage Flash (MSF) and Reverse Osmosis (RO) for the production of water. The energy sub-system considers power generation from a combined cycle gas turbine plant (CCGT) and renewable energy from solar Photovoltaics (PV).

The baseline scenario uses the CCGT to power all water and food sub-systems. The second scenario integrates solar photovoltaic (PV) to power the RO desalination plants. The third scenario uses solar PV to power RO desalination plants and fertiliser production facilities including the water requirement for fertiliser manufacture as illustrated in Table 2.

The subsystems are related to one another through their inputs and outputs. For example; the input of the water subsystem is in the form of kWh/m^3 and the output is in m^3. The input into the combined cycle gas turbine is in the form of kg/MWh whilst the output is MWh. Therefore, the quantity of natural gas (kg) can be calculated per m^3 of water.

Whilst land allocation and suitability for the different crops for the conditions in Qatar continues to be studied, the potential location of food production farms is yet to be determined (QNFSP, 2013). For this reason, the energy required for the distribution of water (horizontal pumping) in irrigation has not been considered in this case study. The scenario analysed excludes the use of groundwater for irrigation, and so the energy requirement for vertical pumping has also not been considered in the analysis. Additional energy requirement for support activities, such as food processing facilities and administrative buildings, which will depend on post-development operational characteristics, are not considered for simplicity. Furthermore, the embodied energy of equipment which would vary for different farms (tractors, on farm machinery and greenhouse construction) has also not been considered at this stage. Within the food sub-system, emissions associated with the import of crops outside the crop profile consumed domestically were not considered and neither was the domestic transport of products. The study also assumes that irrigation supply equals evapotranspiration, given Qatar's climatic conditions. This, in turn, suggests that nitrogen loss through nitrate leaching and the associated emissions are less significant and may be excluded for simplicity. Finally, the land footprint of desalination facilities, power plants and fertiliser production facilities were not considered as this is very small in comparison to the PV and agriculture.

The following sections describe the design of the LCI models for each EWF sub-system and component processes.

3.1. *Energy sub-system*

The LCI models developed for energy production in the EWF assessment tool cover non-renewable energy production from natural gas and renewable solar PV based power generation.

Table 3 – Natural gas composition used to represent gas quality from the Qatar North Field.

Species	Volume (%)
Methane (CH_4)	95.2
Nitrogen (N_2)	1.3
Carbon dioxide (CO_2)	0.7
Ethane (C_2H_6)	2.5
Propane (C_3H_8)	0.2
Butane (C_4H_8)	0.1

3.1.1. *Combined cycle gas turbine LCI model*

The combined cycle gas turbine (CCGT) LCI model developed uses a reference unit of 1 MWh and is based on a Brayton cycle based topping cycle and a Rankine cycle bottoming cycle published by Ibrahim and Rahman (2012). The power plant modelled consists of a compressor, combustion chamber, turbine and power generator. Initially, air is drawn in by the compressor and is delivered to the combustion chamber after which natural gas fuel is used to increase the temperature of the compressed air through the combustion process. Hot gases leaving the combustion chamber expands in the turbine producing work. The waste exhaust temperature from gas turbines decreases as it flows into the heat recovery steam generator (HRSG). The HRSG supplies steam to the steam turbine to generate more work. The model considers the effect of operating parameters such as peak pressure ratio, gas turbine peak temperature ratio, isentropic compressor efficiency and air fuel ratio on the overall plant performance. The model developed assumes a fuel to air equivalence ratio at 0.85 and calculates a total thermal efficiency in the range of 50%–60% in line with literature and industry data. When the nexus energy requirements are set, the CCGT model is used to calculate the quantity of natural gas required to meet the demand. In this regard, the CCGT model calculates a natural gas consumption of 130–135 kg of natural gas to deliver 1 MWh of electricity using the natural gas composition shown in Table 3, which is relevant for gas produced in the Qatar North field.

Furthermore, the LCA model developed by (Korre et al., 2012) which can be used to evaluate the performance of various CCGT power generation plant configurations has been integrated with the thermal efficiency calculations in order to complete the LCI database with a spectrum of emissions from power generation (Fig. 4). The LCI models developed by Korre et al. (2012), besides the conventional CCGT plant, also include the CCGT plant with post-combustion CO_2 capture, power plant that operates Steam Methane Reforming (SMR) with H_2 membrane reactor, and Auto-thermal Reforming (ATR) power plant with Pressure Swing Adsorption CO_2 capture. Nevertheless, this work adopts the emission profile for 1 MWh of generated power without the use of CO_2 capture technology.

3.1.2. *Solar photovoltaics LCI model*

The solar PV LCI model developed uses the RET screen photovoltaic model (RETScreen, 2004). This model considers

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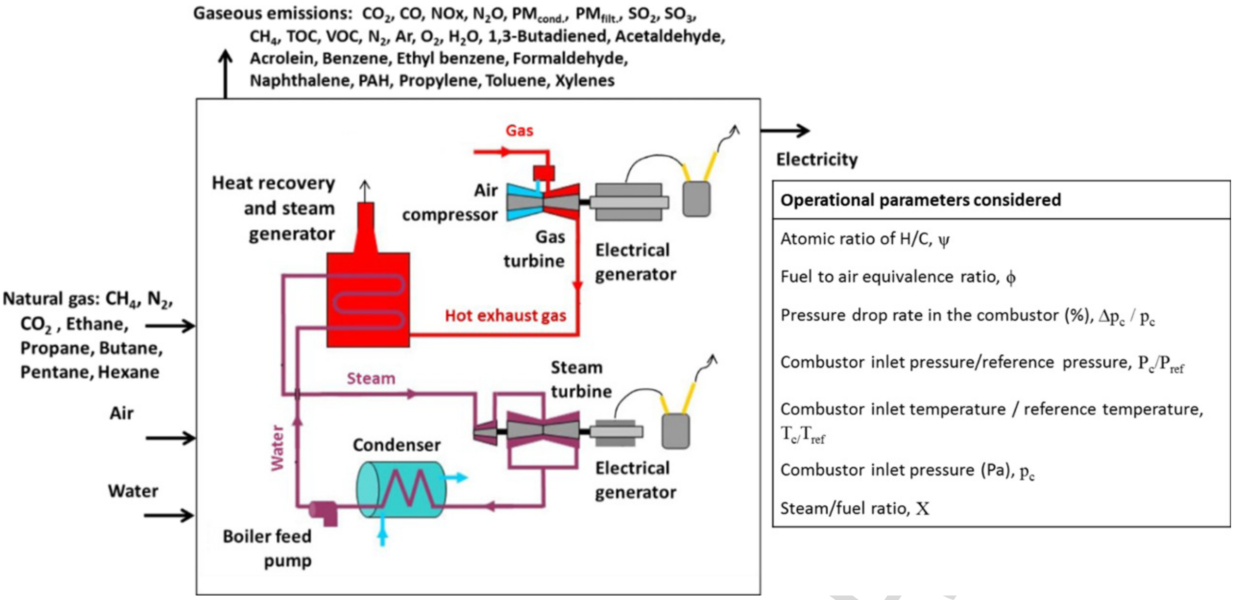

Fig. 4 – CCGT LCI model unit processes, inputs and outputs.

on-grid applications utilising monocrystalline-silicon PV modules, as it is assumed that the solar source and end user will be located in different locations, in which case the grid will act as a medium for the dumping of electricity from the solar PV and the subsequent extraction from the desalination units. In actual fact PV systems have few components in comparison to other power generation systems, such as the CCGT; however, the behaviour of the PV is non-linear and complex in nature. The LCI model developed uses a 100 MW solar power plant as a reference unit with the capability of calculating the power delivered to the grid. The number of power plants required for a scenario can be determined given the total nexus energy requirement for the given scenario.

The calculation of hourly irradiance in the plane of the PV array, H_t is performed using the isotropic model which stipulates that the radiation on the tilted surface of the PV module is considered to include three components: Beam, isotropic diffuse, solar radiation diffusely reflected from the ground (Liu and Jordan, 1963):

$$H_t = H_b R_b + H_d\left(\frac{1+\cos\beta}{2}\right) + H\rho\left(\frac{1-\cos\beta}{2}\right). \tag{1}$$

Where; H_t is the hourly irradiance on the plane of the PV array, H is the global horizontal irradiance, H_b is the beam irradiance component, H_d is the diffuse irradiance component, ρ represents the diffuse reflectance coefficient from the ground, β represents the slope of the PV array and R_b is the ratio of the beam radiation on the PV array to that of the horizontal.

The daily global horizontal irradiance is then translated into an electricity conversion potential. Initially, the PV module efficiency (η_p) is calculated as a function of the average module temperature (T_c), which is dependent on the nominal operating cell temperature (NOCT) and the clearness index (K_t).

$$E = \eta_p \times H_t \times 30 \times A. \tag{2}$$

Where; 30 is the number of days per month and A is the area of the plant. Note; the area is dependent on the watts per module, area of module and power plant capacity (e.g. 100 MW). The life cycle emissions for solar PV are also considered (Fthenakis and Kim, 2011). Emissions are released during other phases during the lifetime of the PV module which includes the fossil-fuel energy required to make materials for solar cells, modules and smelting, production and manufacturing facilities. The emissions from these sources vary considerably depending on the electricity make-up of the source country (for Qatar this is CCGT as estimated using the LCI model of the present study).

The 100 MW photovoltaic power plant consists of monocrystalline-silicon PV modules with an embodied energy of 31,244 GJ/MW and a 30 year lifetime (Ito et al., 2008). The indirect natural gas requirement, energy and emissions associated with the PV module manufacture are calculated using the CCGT sub-system model. The main performance indicators that will need to be determined:

$$EPT = \frac{\text{Total lifecycle primary energy requirement of the PV system}}{\text{Annual primary reduction by using PV system}}. \tag{3}$$

The EPT is the energy payback time (years) and calculates the years to recover primary energy (fossil fuel) consumption throughout the life cycle by clean energy production.

It will be assumed that all manufacturing local and the electricity grid is 100% natural gas based as described in section. Furthermore, the CO_2 emission rate demonstrates the usefulness of the PV in reducing global warming.

$$CO_2 E.R. = \frac{\text{Total } CO_2 \text{ emission on lifecycle (g-C)}}{\text{Annual power generation} \times \text{Lifetime}}. \tag{4}$$

Where; CO_2 ER is the emission rate measured in (g-C/kWh) and annual power generation is measured in kWh/year.

3.2. *Food sub-system*

The food nexus element encompasses two main sub-systems: fertiliser production (organic and inorganic) and the agriculture sub-system. The two sub-systems are related to one another through the nitrogen cycle (Galloway, 1998; Galloway et al., 1995; Jenkinson, 2001). The analysis of the nitrogen cycle can give a local, regional or national indication as to the environmental degradation that has taken place due to anthropogenic activities. However, the analysis of the nitrogen cycle is not within the scope of this work and only the sub-systems related to the production of fertiliser and the raising of livestock are considered. Furthermore, the direct N_2O emissions from the agricultural soils have not been considered for simplicity.

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3.2.1. *Fertiliser production LCI model*

The production of fertilisers is one of the most important aspects to consider in an LCA evaluating the environmental impact of food production. Crops need nutrients to grow which can originate from either organic (manure, residues, soil organic matter) or from mineral fertilisers. The availability of plant nutrients in sufficient amounts and their correct balance is fundamental for optimising the yield. Mineral fertilisers can be based on nitrogen (N), phosphate (P_2O_5) and potash (derived from marketable KCl containing approximately 60% K_2O). Together, fertiliser production consumes approximately 1.2% of the world's energy and is responsible for approximately 1.2% of the total emission of the greenhouse gases, consisting of 0.3% of pure CO_2, 0.3% as N_2O and 0.6% as flue gas CO_2. The main energy requirement for production of fertilisers is linked to the nitrogen component; 94% for N, 3% for P_2O_5 and 3% for the K_2O component on a global basis (Jenssen et al., 2003).

Energy efficiency has gone a long way in reducing fertiliser production footprints. Although the objective of this work is not to evaluate process options for the further improvement of energy efficiency in such plants, it is recognised that unless inventory models are constructed using country specific data (including the composition of natural gas and electricity mix for power supply from the grid) and production plant specific information, it is difficult to accurately account for all the emissions from the production of the full range of fertilisers used in a food system.

For this study the production and application of urea which is manufactured from ammonia is considered for the quantification of emissions. Full assessment would require the integration of emissions from other fertilisers used within the agriculture subsystem such as those derived from; natural gas (ammonia and nitric acid based), phosphorus and sulphur. However, urea only is considered, because it is manufactured locally and the relevant data was available for this work. Individual models using 1 tonne of ammonia and subsequently 1 tonne of urea as reference units were developed. The models integrate mass balance calculations with plant data and emission factors were developed to calculate the emissions and resource consumption for urea production. The electricity requirement encompasses the power required to drive the process and to convert water into steam. Regarding the GHG emissions from fertiliser application, updated emission factors from the work of Brentrup and Pallière (2008) are utilised. The emissions include; urea hydrolysis (the release of CO_2 after application, equivalent to the CO_2 fixed during production), direct N_2O from use, indirect N_2O via NH_3, indirect N_2O via NO_3 and CO_2 from liming.

Ammonia production

Ammonia synthesis is based on the Haber Bosch method which has seen significant improvements in operating energy efficiency. Modern plants can produce up to 1,500 MTPD in which 77% of plants use natural gas as feed. Natural gas is used as the feed for one of two processes, either partial oxidation or steam reforming, which is adopted by 85% of ammonia plants globally (EFMA, 2000b). The ammonia LCI model developed for this work involved developing a material balance calculation and integrating energy and steam data from an existing plant. Production using the steam reforming of natural gas is the process simulated. Six process steps are required to produce synthetic ammonia using the catalytic steam reforming method (1) natural gas desulphurisation, (2) catalytic steam reforming, (3) carbon monoxide shift, (4) carbon dioxide removal, (5) methanation, (6) ammonia synthesis. The configuration of the units in sequence allows the calculations of emissions at every unit stage (EFMA, 2000b). Energy and steam data was integrated using plant data for an existing 1000 MTPD Ammonia facility (Dybkjaer, 1990) and a local plant in Qatar (personal communication QAFCO Qatar Fertiliser Company, 2011).

Urea production

Urea has the highest nitrogen content available in a solid fertiliser with 46%. The synthesis of urea involves the combination of ammonia and carbon dioxide at high pressure to form ammonium carbamate, which is subsequently dehydrated by the application of heat to form urea, 70%–77% aqueous solution (EFMA, 2000a).

$$2NH_3 + CO_2 \leftrightarrow NH_2COONH_4 \leftrightarrow CO(NH_2)_2 + H_2O.$$

The urea synthesis reactor always contains unreacted carbamate and excess ammonia depending on the composition of the feeds. The conversion on CO_2 basis is usually in the range of 50%–80% in which unreacted material would be recycled in different processes such as the Snamprogetti or the Mitsui Toatsu process. The model developed does not consider any recycling loops, as such conversion was assumed to be 100% on CO_2 basis.

Partial conversion occurs in the reactor where a urea solution consisting of urea, carbamate, water and unconverted CO_2 and NH_3 is then fed into a stripper adopting one of the technologies above. The urea solution from the stripper is then sent to the first stage decomposer, where urea purification takes place by the dehydration of the carbamate; after which it is then passed through second, lower pressure decomposer for further purification.

The resulting urea solution from the LP decomposer is then sent to the vacuum concentrator which reduces the water content in the urea to as low as 1%. Finally, the resulting 98% molten urea is sent to the prilling stage, where urea prills are formed. The model developed for this study is a simple mass balance consisting of the above units described above and was calibrated to the plant data used in the previous ammonia production facility (Dybkjaer, 1990). The model is designed in a way such that additional CO_2 is added in order to ensure the all the NH_3 is reacted. The process flow is summarised in Fig. 5.

3.2.2. *Livestock management LCI model*

Animal production systems transform carbohydrates and protein from animal feed into consumable items such as eggs, milk and meat. However, there are important waste emissions from this process which need to be integrated into the nexus model and allocated to the relevant LCA impact categories. It is important to consider cattle/livestock due to their high population and the corresponding high CH_4 emission rate from their ruminant digestive system. It is estimated that livestock production is responsible for approximately 18% of the world's anthropogenic GHG emissions (Weiss and Leip, 2012). Furthermore, wastes from animal production systems contribute as much 30%–50% of the global N_2O emissions from agriculture. A number of livestock systems analysis and LCA studies have been reported in literature (Sandars et al., 2003; Oenema et al., 2005; Schils et al., 2006; FAO, 2010; Hishinuma et al., 2008) for which different emission sources and system boundaries are defined. GHG emissions from manure depend on the management method, temperature, amount

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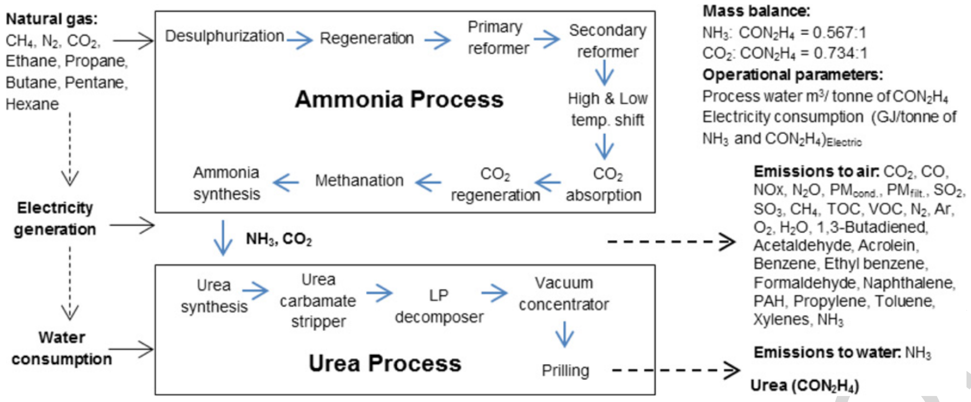

Fig. 5 – Ammonia and urea processes LCI model, inputs, outputs and key operational parameters.

of manure and its constituents. This study considers two manure storage types management types; the storage of manure in liquid systems and solid storage (drylot) as described in IPCC (2006).

A number of factors affect the emission of gases and particulate matter from animal feed operations (AFOs). Most of the substances emitted are the products of microbial processes that decompose the complex organic constituents of manure. The emissions from AFOs depend on manure characteristics such as its nitrogen and moisture content. The differences in production and management practices for different animal sectors result in different microbial environments leading to varying emission profiles which consist of CH_4, N_2O, NH_3, H_2S and PM_{10}, VOC compounds and odours. The CO_2 emission from livestock was not considered because it is assumed that the annual net CO_2 emissions are assumed to be zero. The CO_2 from animal manure is a release of carbon sequestered by photosynthesis. However, the portion of carbon returned as CH_4 need to be considered as discussed next.

The quantification of the GHG fluxes for all emission sources used in this work follow the IPCC (2006) Tier 1 guidelines. More accurate analysis would involve the use of the Tier 2 and Tier 3 guidelines. However such analysis would require additional information on the tract, age, weight of the animal and both the quality and quantity of the feed consumed, which is not available. It is important to note that there are significant uncertainties associated with the use of default emission factors such as those used in the IPCC (2006) Tier 1 analysis which will be addressed. The principal emissions with a GWP from the livestock sub-system include CH_4 which is released from enteric fermentation and both CH_4 and N_2O (direct and in-direct) are released from manure management systems. Whilst this study assumes that all CH_4 is allowed to be released into the atmosphere, some livestock management systems are equipped to capture the CH_4 to be re-used as a source of fuel. Furthermore, in-direct emissions of N_2O (Volatilisation of NH_3) from nitrate leaching have not been considered.

Emission factors from virtual farms are used in the compilation of the LCI for the non GWP related emissions. The emissions include NH_3, VOC compounds, H_2S and PM_{10} which feature in the human toxicity and potential for acidification categories. The virtual farms which were used to compile the emissions are a combination of different confinement facilities, manure collection systems and manure storage practices. Food system emissions are expected to vary depending on the manure management facility employed and the emission factor used for the inventory. As such a sensitivity analysis with a 50% range for the emission factors is used to access whether variations in emission factors have an influence on the overall trend on the nexus performance results (Spellman and Whiting, 2007).

3.3. *Water sub-system*

In the Middle East there is a tendency for water production systems to be coupled with power plants due to the similar growth patterns in both water and energy demand. Thermally operated desalting plants which are coupled to power plants obtain their heat input as steam supply, either extracted from a steam turbine or from the heat recovery steam generator (HRSG) in a combined cycle power generation system utilising a gas turbine (CCGT). With increasing water demand in isolation to power and improved anti-fouling/scaling membranes, the desalination of water using Reverse Osmosis (RO) is increasing. Furthermore, the specific energy requirement of RO systems is significantly lower than for other desalination technology options. For instance thermal desalting systems such as Multi-Stage Flash (MSF) consume specific mechanical equivalent energy of about 4 kWh/m^3 of desalinated water, and heat energy in the range of 20 kWh/m^3, whilst RO desalting systems reduce the total energy requirement to 4–6 kWh/m^3 (Darwish and Al-Najem, 2000). Darwish et al. (2009) explored the true impact on the environment by considering the actual fuel consumption and the associated emissions from the provision of water from a variety of different power and water configurations. These authors concluded that a GT/ST (CCGT) driving an RO is the most energy efficient and requires the least amount of fuel for a given desalting capacity as confirmed in Table 4.

The EWF nexus model considers different energy and water configurations were re-engineering and integrated into the nexus tool developed in this work. This was done in order to provide flexibility when selecting the method of water provision and allowing for input parameters such as seawater salinity to be case specific. This report will only detail the use of mechanical energy from renewable and non-renewable sources to drive a reverse osmosis (RO) system.

Osmosis is a natural process involving fluid flow across a semipermeable membrane barrier. Solvents pass through the membrane faster than dissolved solids therefore resulting in a solvent–solid separation. Osmotic flow from the pure water side across the membrane to the salt solution side will occur until equilibrium is reached where the hydrostatic pressure differentiation resulting from the volume changes on both sides is equal to the osmotic pressure. Application of an external pressure to the salt solution side equal to the

Table 4 – Summary of the desalted water output *D* and total specific fuel energy Q_f/D for 14 studies considered by Darwish et al. (2009).

No.	Case	D for Q_{ref} (kg/s)	(Qf/D) (MJ/m^3)
1	Fuel Fired boiler driving TVC	314.6	329.4
2	Fuel fired boiler driving MSF	332.2	311.9
3	Steam extracted from steam turbine driving MSF	522.0	198.5
4	BPST power driving mechanical vapour compression (MVC) and multi-effect desalting (MED)	803.2	129.0
5	BPST power driving SWRO and MED	1459.9	71.0
6	Steam cycle driving MVC	863.6	120.0
7	Steam cycle driving sea water reverse osmosis (SWRO)	1727.1	60.0
8	GT driving SWRO	1775	58.4
9	GT driving MVC	887.2	116.8
10	GT with HRSG driving MSF and SWRO	1824.7	56.8
11	GT/ST cycle driving SWRO	2514.0	41.2
12	GT/ST cycle driving MVC	1256.0	82.5
13	GT/ST cycle with BPST driving MVC and MED	2579.5	41.9
14	GT/ST cycle with BPST driving SWRO and MSF	2,427.0	42.7

osmotic pressure (proportional to the total dissolved solids in the intake water) will also yield equilibrium. Reverse osmosis is when there is an application of a pressure larger than the osmotic pressure. In this case, the chemical potential of the water in the salt solution causes a solvent flow to the pure water side since it has a lower chemical potential (Wilf et al., 2007).

The RO model that was developed as part of this study (Fig. 6) consists of a one stage pass system using the SWC 4+ membrane, such the energy and fuel requirement per m^3 of desalinated water for the salinity characteristics of any intake of seawater is calculated (Wilf et al., 2007). The energy requirement is a function of the net driving pressure (NDP), which is the driving force through a semi-permeable membrane, defined as the fraction of the applied pressure in excess of the average osmotic pressure of the feed and any pressure losses within the system. Q6

$$NDP = P_f - P_{os} - P_p - 0.5P_d + P_{osp}. \tag{5}$$

Where; P_f is the feed pressure, P_p is the permeate pressure, P_d is the pressure drop across RO elements and P_{osp} is the osmotic pressure of intake.

Once, the feed pressure has been estimated, the feed pump power consumption can be estimated (Darwish and Al-Najem, 2000):

$$W_p = Q_f \times \frac{\Delta P}{\eta p \times \eta m}. \tag{6}$$

Darwish and Al-Najem (2000) considered an extra 20% energy consumption, which accounts for seawater supply, seawater boost and chemical dosing pumps. Furthermore, a Pelton wheel energy recovery device with 65% efficiency was integrated. With seawater data for a coast in Qatar used as input data into the RO model, the specific energy consumption E calculated is 4.5 kWh/m^3. The specific fuel consumption is then calculated using the following relationship:

$$D = \frac{P}{E}. \tag{7}$$

Where; *D* is the RO water output, *P* is the power output from the CCGT model and *E* is the specific energy of the RO unit.

$$e = \frac{Q_f}{D}. \tag{8}$$

Where; *e* is the total specific fuel energy, Q_f is the fuel input rate from the CCGT model. Q7

3.3.1. *Water requirement within the EWF nexus*

It is assumed that desalinated water is used within the nexus. The water requirement within the food subsystem is mainly governed by the irrigation requirement and what is consumed during fertiliser production. The water requirement for fertiliser production used in this work, which encompasses processed water and steam, is based on plant data from a local producer. Within the energy subsystems, water consumption in thermoelectric generation systems is used to drive a steam turbine and for cooling purposes to condense the steam. The source of water varies for different regions depending on the availability of fresh water. For the purposes of this study it is assumed that the water utilisation factors for a closed loop CCGT power plant and PV (negligible) are based on. The water requirement factor for energy production used is 0.8775 m^3/MWh (Mielke et al., 2010).

3.4. *Estimation of integrated brine environmental impact factor for the Arabian Gulf*

The Arabian Gulf is a shallow semi enclosed marginal sea with one of the highest recorded salinities in the world. It covers an area of about 240,000 km^2, has a mean depth of 35 m and is 1000 km in length with widths that range from 185 km to 370 km. It is connected to the Gulf of Oman via the narrow Strait of Hormuz with fresh water inflows from the Tigris, the Euphrates and the Karun at the Delta of Shatt al Arab estimated at 0.2 m/yr (Michael Reynolds, 1993). The mean evaporation rate is estimated approximately at 1.5 m/yr. It is important to note that there is variation with respect to the characteristics of the Arabian Gulf summarised above.

More than 50% of the world's desalination capacity is situated in the Arabian Gulf. Desalination is a very energy intensive process in which the energy is required to separate fresh water from the seawater and the resultant concentrated brine is rejected back to the sea. The rejected concentrate does not only contain its initial intake content, but it also contains the additives required for the pre-treatment, desalting process and corrosion by-products. As such, there are numerous environmental impacts associated with desalination (Darwish et al., 2013; Hoepner and Lattemann, 2003):

- entrainment and impingement of marine organisms at the seawater intake,
- negative impacts of the brine discharge with its chemical contaminants to sensitive marine habitats,

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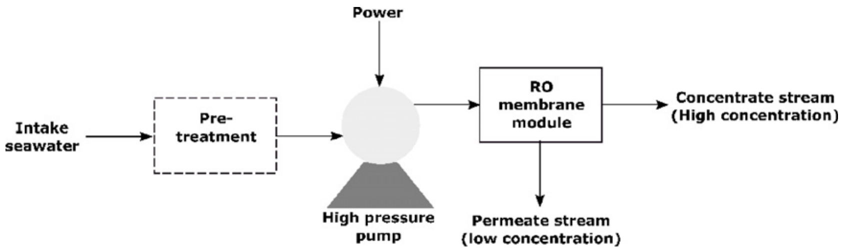

Fig. 6 – RO system diagram, input and emissions.
***Source:* Adapted from Wilf et al. (2007).**

- high energy use to produce desalted water,
- impacts on biological resources and habitats,
- the cumulative impact of the numerous desalination plants on the Arabian Gulf and the associated uncertainty.

Pre-treatment is necessary in order to decrease the turbidity (suspended solids) and the quantity of organic and inorganic foulants acceptable for desalination equipment whilst producing high quality potable water (Darwish et al., 2013). The types and amounts of the chemicals used depend on the chosen technology (mechanical or thermal) and the required quality of product. In membrane processes, pre-treatment is extensive as it involves filtration to remove suspended solids (particles, silt, organics, algae, etc.) in addition to oil and grease contained in the salt water. In thermal processes such as MSF, pre-treatment protects downstream piping and equipment from corrosion and from formation of excessive scale hard deposits on piping surfaces (known as scaling) (Darwish et al., 2013). Considering RO, the membranes are not tolerant to direct operation with open seawater without pre-treatment. Conventional pre-treatment technology relies on a combination of chemical treatment and media filtration to achieve the required feed water quality for the membranes (Darwish et al., 2013; Lattemann and Höpner, 2008):

- Biofouling: Residual chlorine neutralisation is used before the water enters the RO units to avoid membrane damage since the RO membranes are typically made of polyamide materials, which are sensitive to oxidising chemicals such as chlorine. Sodium bisulfite ($NaHSO_3$) is used for dechlorination.
- Coagulation/media filtration: It is necessary to remove suspended materials from the RO feed stream since they can cause irreversible damage to the membranes. For granular media filtration, the dosing of a coagulant is required. Coagulants such as $FeCl_3$ or $AlCl_3$ are metal salts which form dense suspended solids as they react with hydroxides in aqueous solutions.
- Anti-scaling: Control of scaling is achieved by means of acid addition, usually H_2SO_4 or HCl, used to lower the pH (6–7).
- Cartridge filters: The feed water is passed through a 5 µm cartridge filter before entering the RO units in order to remove any remaining traces of suspended solids and microorganisms.

3.4.1. *Integration of brine effects in LCA*

Different treatments applied to the intake water of desalination facilities will result in the addition of various chemicals which will appear in the reject concentrate. Therefore, it is important to consider the chemical composition of the brine discharged into the sea in addition to its thermal characteristics and salt concentration. As such, in addition to the baseline LCA impact categories, the local environmental impact from brine discharge on the Arabian Gulf should be integrated into the nexus model. The available literature on this subject is limited. This is because the complexity and variation in the discharged brine composition is very significant and the required data acquisition to support the assessment is challenging (Zhou et al., 2012). Essentially, the composition of brine is a function of the feed water, pre-treatment and the desalination process, containing residuals of anti-fouling, anti-scaling and chemical additives, metal ions, concentrated constituents such as Na^+ and Cl^- and other contaminants such as boron.

The methodology used in this work integrates both the high demand chemical by chemical approach with the less data intensive but less accurate whole effluent approach in what is known as the group by group approach. This approach calculates the average aquatic ETP impact as the sum of impacts generated by acknowledged groups of influential chemicals.

$$\text{AquaticETP of brine disposal} = \sum m(\text{group}j) \times \text{CF}^{\text{aquatic ETP}}(\text{group}j). \qquad (9)$$

Where, m (group j) is the mass of the acknowledged group j and $\text{CF}^{\text{aquatic ETP}}$ (group j) represents the aquatic eco-toxic characterisation factor for group j.

3.4.2. *Arabian Gulf salinity consideration:*

With respect to the regional impact, there is great uncertainty regarding the effect brine discharge has on the overall salinity of the Arabian Gulf. The predictive capability regarding this issue is limited. The mathematical model developed by (Purnama et al., 2005) is one example of how salinity in the Arabian Gulf has been analysed to date. The Arabian Gulf is modelled as a semi-enclosed sea with simple depth topography. Using a mass flux balance for water and an advection–diffusion relationship the logarithm of relative salinity Δs, due to seawater desalination facilities is expressed as:

$$\ln\left(1 + \frac{\Delta s}{s*}\right) = \sum_{i}^{n} (1 + r) Q_i \int_{\max^{l}(x, a_i)}^{l} \frac{dz}{AD}. \qquad (10)$$

Where A is the cross sectional area, s^* is the maximum salinity, r is the recovery rate, Q is the volume of intake water and D is the tidally averaged shear dispersion coefficient.

For the nexus model, the total desalination capacity was considered for five countries (Qatar, Saudi Arabia, Kuwait, United Arab Emirates and Bahrain) located at fixed locations within the Arabian Gulf (Al Barwani and Purnama, 2008). The total baseline capacity encompassed all desalination technologies (thermal and mechanical) with an approximate total of 5,000 mm^3/y. The initial maximum salinity used in the model was 40 ppt. It was assumed that the desalination

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capacity for each country increased in the same proportion to population rate from the baseline (2010) to the scenario year of 2025 (Bashitialshaaer et al., 2011). It is important to note that the RO model developed for the Qatari food system assumed a fixed salinity for the intake seawater. This is because it is unclear how a recorded increase in salinity in the Arabian Gulf to a new maximum calculated from the model would be transmitted to the coastal waters of Qatar.

4. Assessment of the environmental impact of Qatar's energy, water, food nexus

The inventory models presented were used to calculate life cycle environmental impact of Qatar's energy, water and food nexus for the baseline scenario, the scenario of PV Integration for the water system and that of PV integration for both water and food systems examining the mean, upper and lower range of impacts for each life cycle impact category considered. The results indicate that the largest GWP originates from the food nexus element (Fig. 7) which illustrates nexus results for the two manure management systems considered. It is shown that in the liquid slurry manure management system using, the non-energy related emissions contribute about 60%, 75% and 99% of the total emissions in the baseline, PV for water sub-system and PV for water and food sub-systems scenarios respectively. Non-energy related emissions from the food subsystems do not change across the different configurations. However, the energy related emissions for the water and food subsystems vary depending on the configuration utilised. Furthermore, only energy related processes within the water subsystem release greenhouse gases, therefore non-energy related emissions are not presented in Fig. 7. Upper, mean and lower estimates do not change across scenarios for the same manure management system.

The largest share of these emissions emanates from the livestock sub-system representing a share of over 90% and is consistent over the three scenarios based on the type and quantity of livestock under management. Furthermore, the methane emissions from enteric fermentation and manure management systems represent over 95% of the emissions from the livestock sub-system with liquid slurry or solid storage based management performing better than the dry lot manure management option. It is important to note that even when utilising the lowest range of emission factors from the livestock sub-system, the respective emissions remain the largest with no shift in trend.

With respect to the human toxicity impact category, it is evident that varying emissions of NH_3, PM10 and VOC compounds from the livestock sub-system within a range of 50% has minimal impact on the total human toxicity potential as illustrated in Fig. 8. The largest source of emissions emanate from the energy using sub-systems which include the desalination facilities and production of fertilisers whilst the non-energy related emissions from the water subsystem are negligible.

The acidification potential does not show any significant variation in trend amongst the three scenarios as illustrated in Fig. 9. This is because the single largest contributor to the acidification potential is the NH_3 emissions from the livestock sub-system, which are consistent amongst the three scenarios examined, whilst the non-energy related emissions from the water subsystem are negligible. The integration of PV to power the water sub-system reduces the GWP by 24%. A larger roll out of PV to power the entire nexus system (water and food sub-systems) would reduce the GWP by approximately 30% from the baseline scenario. The life cycle of the PV module has been considered such that the energy payback period for the manufacture of the PV module is 3 years. The introduction of solar PV entails a land investment as illustrated in Fig. 9.

The lower limit for each scenario considers only the area of the modules while the upper limit uses the typical size of a single 100 MW solar power plant as a standard multiplied by the number of plants required for the scenario. Considering the natural gas requirement to support Qatar's EWF nexus (Fig. 9), natural gas use for the manufacture of ammonia is negligible in comparison to the use of natural gas for power generation. As PV roll out replaces the power needs on CCGT, natural gas use reduces significantly (Fig. 9). In the full PV roll out scenario, approximately 8 PV power plants with a total area of 5 km^2 or 500 ha are required (roughly equivalent to 450 full size football pitches). Furthermore, the natural gas used to manufacture the PV modules represents 97% of the total natural gas requirement.

The reverse osmosis driven food system can increase the aquatic eco-toxicity impact of Qatar's coastal regions by approximately 2.5% from the baseline scenario which assumes that current capacity in Qatar is supplied through the multi-stage flash (MSF) desalination process. Considering regional effects of desalination, the advection–diffusion model predicts that the maximum salinity of the Arabian Gulf will rise. The contribution of the food system RO desalination facilities to the perceived overall trend in the first year of operation (2025) is 0.15% which according to the advection–diffusion model is expected to continue to increase. However, it is unclear if this theory is entirely applicable in real situations. This is because when evaluating real data from the Regional Organization for the Protection of the Marine Environment and historical data dating from 1923–2006 it is unclear if the evidence supports significant differences in salinity within the Arabian Gulf (ROPME, 2010). Furthermore, important factors including seasonal or latitudinal salinity variations, atmospheric mixing forces and coastal currents are not considered, and the oceanographic circulation systems of the Arabian Gulf are too complex to be simply represented through a 1-D model. Additional uncertainties regarding the boundary condition (fixed salinity at the Strait of Hormuz) and the water volumes crossing the Hormuz weaken the modelling assumptions. Therefore, it is concluded that although the model cannot provide conclusive prediction on the salinity evolution of the Arabian Gulf, it can be used sensibly to compare systems states or scenarios.

5. Conclusions

In light of global uncertainty regarding resource scarcity, climate change and competition for food from a growing population, it is necessary that policy makers of any nation evaluate all options for ensuring the continuous supply of food. One such action is the raising of the domestic production. Increasing domestic food production to 40% still implies that the remaining 60% of national requirements would be sourced from the global markets. In this regard, the diversification of levers for the provision of food will ensure resilience in the national strategy and safeguard the right of all people to a safe, continuous and nutritious supply of food.

The model presented in this work demonstrates the importance of integrated modelling in evaluating the

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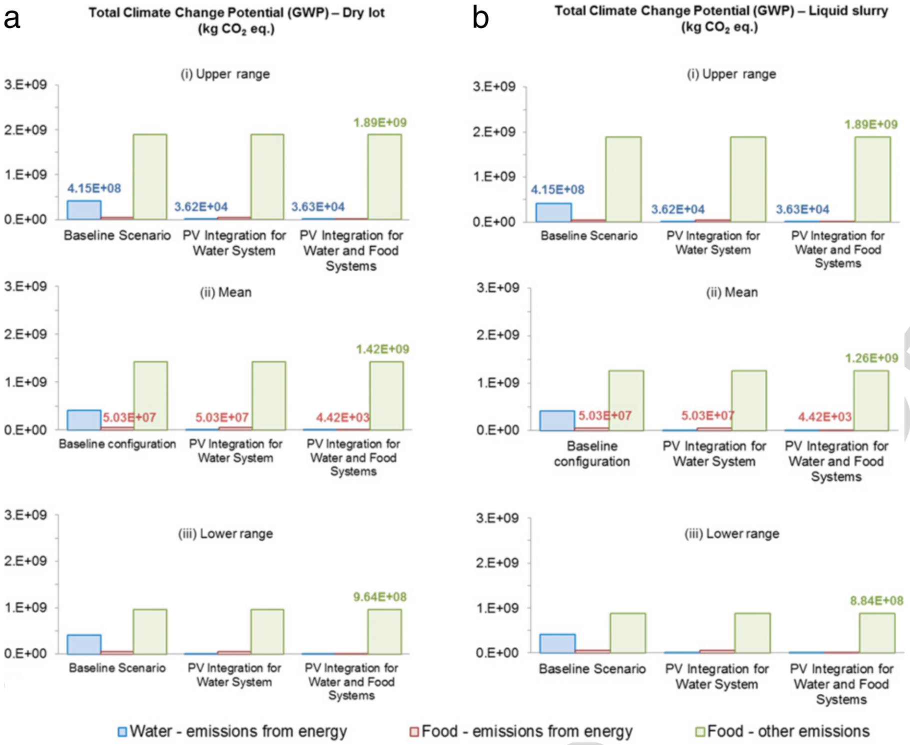

Fig. 7 – Total GWP for Qatar's EWF nexus system for (a) 100% utilisation of a dry lot manure management system and (b) 100% utilisation of liquid slurry based manure management system.

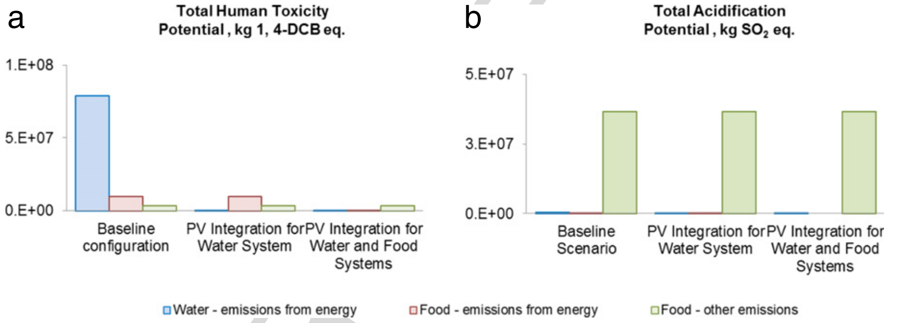

Fig. 8 – (a) Total human toxicity and (b) acidification potential for Qatar's EWF nexus system.

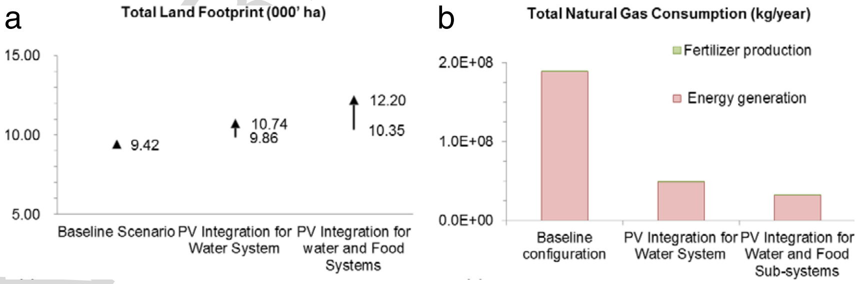

Fig. 9 – Total land footprint (a) and natural gas requirement (b) for Qatar's EFW nexus system.

environmental impact of different EWF scenarios when delivering a product or a service. The EWF nexus tool developed was used to evaluate the environmental impact of expanding food production to a perceived level of food security for the State of Qatar. The EWF analysis presented in this study utilises LCA and the aggregation of resource sectors into sub-systems to develop a tool that will identify the largest sources of ecological and human impacts. Evidently, the emissions from the sub-systems within the food nexus element represent the largest sources of degradation. The emissions emanating from within the livestock sub-system are shown to be the overwhelming contributors to global warming and acidification potential.

As the crop profile and sub-systems used in this study are unique in nature, it is difficult to provide a comparison with previous case studies. Although the emissions from within the livestock subsystem represent the largest uncertainty, it is also demonstrated that utilising upper and lower ranges for emission factors does not change the overall trends. Opportunities to reduce the net impact on the environment can be sought by either focusing on methods to reduce the emissions from the live-stock sub-system or by enhancing the

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performance of the other sub-systems in order to compensate for the emissions from the livestock sub-system.

A key feature of the EWF nexus methodology is the capacity to relate resource consumption in delivering a product or service to national resource capacity in addition to the overall life cycle impact. Modularising processes in the form of subsystems in the development of the LCI is a prerequisite to building in flexibility within the EWF tool. This will ensure that the EWF tool can be reconfigured to consider different geographical applications for food production or for different products utilising the same subsystems. Furthermore, analysis using the EWF nexus allows the integration of multiple product systems. Such analysis can create a blueprint for total material and energy flow depicting the parallel relationship between product systems and supporting subsystems (energy, water and food). Furthermore, it becomes possible to evaluate the trade-offs that would need to be considered when producing a range of different products within the same environment. To carry out a reliable assessment, the detail of relevant subsystems need to be incorporated in the analysis. This will enable the identification of opportunities for process integration in the manufacture of a single product in addition to integration opportunities across different products, which utilise the same subsystems and within the same environment.

A complete sustainability assessment can only be achieved with the integration of a robust economic model through a life cycle costing procedure. An EWF model fitted with a dual environmental and economic assessment capabilities will ensure that trade-offs can be explored for: (1) a range of processing scenarios in the manufacture of a single product and (2) creating a means to which a wide range of products can be prioritised in terms of their economic benefit and their subsequent impact on the environment. Future work will also consider opportunities to increase the environmental performance of the Qatar food system such as the recycling of solid waste into useful forms. The objective of which is to balance the emissions from the food nexus element and the livestock subsystem. Finally incorporating the emissions from the life cycle of imported products would provide an insight into the overall environmental burden of food consumption in Qatar.

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