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Considering the energy, water and food nexus: Towards an integrated modelling approach

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ABSTRACT

The areas of energy, water and food policy have numerous interwoven concerns ranging from ensuring access to services, to environmental impacts to price volatility. These issues manifest in very different ways in each of the three "spheres", but often the impacts are closely related. Identifying these interrelationships *a priori* is of great importance to help target synergies and avoid potential tensions. Systems thinking is required to address such a wide swath of possible topics. This paper briefly describes some of the linkages at a high-level of aggregation – primarily from a developing country perspective – and *via* case studies, to arrive at some promising directions for addressing the nexus. To that end, we also present the attributes of a modelling framework that specifically addresses the nexus, and can thus serve to inform more effective national policies and regulations. While environmental issues are normally the 'cohesive principle' from which the three areas are considered jointly, the enormous inequalities arising from a lack of access suggest that economic and security-related issues may be stronger motivators of change. Finally, consideration of the complex interactions will require new institutional capacity both in industrialised and developing countries.

1. Introduction

Global human society must now attempt to solve a set of complex, interrelated problems that Diamond (2005) characterises as fundamental threats to human civilisation. Many of these issues are directly related to the areas of energy, water and food (EWF[1]) production, distribution, and use—especially in developing countries. As Hague (2010) said, "They form four resource pillars on which global security, prosperity and equity stand."

Still, due to the vastness of the individual areas and the difficulty of considering all three together, there is little work focusing on how to support decision-making at the nexus.[2] As a result, policies and regulations can often inadvertently create sub-optimal signals to economic, national security or environment concerns. Even when policy is designed by considering more than one area, it is normally done with a focus on two areas only (see e.g., Winpenny, 1992), and few approaches have comprehensively addressed the broader interdependencies.[3]

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[1] We will use the term EWF throughout the paper. Still, it is recognised that the term land-use might be a more accurate one for some of the modelling work.

[2] As Murray Gell-Mann is widely cited as saying, "Today the network of relationships linking the human race to itself and to the rest of the biosphere is so complex that all aspects affect all others to an extraordinary degree. Someone should be studying the whole system, however crudely that has to be done, because no gluing together of partial studies of a complex nonlinear system can give a good idea of the behaviour of the whole." We briefly allude to complexity theory in Section 5.

[3] As an example, McCornick et al. (2008) presented a series of aspects related to the nexus, including: energy prices and the economy of water in agriculture, hydropower and irrigation conflicts, bio-fuel expansion and food-security concerns, and the divergence between the role of water in power generation and that of energy in groundwater pumping. Still, a comprehensive framework was not reported and the nexus was treated 'two-at-a-time'. Similarly, the World Economic Forum addressed the EWF nexus in its 2011 Water Security report (WEF, 2011a); again, there is not a quantitative framework presented. Allan (2011) adds to the EWF nexus with issues such as trade and climate change.

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Systems thinking is required—something not easily translated into government policy-making processes.[4] Benefits of more holistic policy and regulatory design would likely be: economic efficiency, resource efficiency, improved livelihood options and public health. Negative consequences can include impacts on communities, to commodity prices, to sub-optimal infrastructure design, to environmental degradation.[5]

These issues are not limited to environmental concerns. There are billions of people that do not have access to good quality services related to energy, water and food. The number of people disadvantaged by this has remained relatively unchanged over recent decades—and that trend (at least in some areas) is predicted to continue. The negative consequences of this are enormous and range from social to economic to security concerns. The access issue is apparent in both rural and urban settings,[6] and we use it as one lens for considering the EWF nexus. The paper provides a rationale for addressing the nexus in a quantitative manner and presents a modelling framework that can support effective policy and regulatory design. Brief case studies are included to underscore the need for this type of analysis and the related institutional changes required. While it remains the case that it is difficult to marry the often short-term and sectoral focus of government decision-making with this type of systems thinking, the current political prioritisation of access issues, allows an opportunity to revisit the need for influential inter-disciplinary analysis. The paper is presented to provide context for future, more detailed research. To that end, we provide extended references to the relevant literature.

2. Interactions

The approach to the energy, water, and food nexus normally depends on the perspective of the policy-maker (Harris, 2002). If a water perspective is adopted, then food and energy systems are users of the resource (see e.g., Hellegers and Zilberman, 2008); from a food perspective energy and water are inputs (see e.g., Mushtaq et al., 2009; UN-DESA, 2011; Khan and Hanjra, 2009); from an energy perspective, water as well as bio-resources (e.g., biomass in form of energy crops) are generally an input or resource requirement and food is generally the output. Food and water supply as well as wastewater treatment require significant amounts of energy. Of course, areas such as food-as-fuels (i.e., biofuels) tend to blur these descriptions (see e.g., Nonhebel, 2005) due to additional impacts associated with land use, land use change and use of the available biomass resource. In any case, the perspective taken will affect the policy design. This is due to the specific priorities of the institution or ministry, as well as the data, knowledge and analytic breadth of the tools of the associated experts and support staff. There are very few people expert in all three areas.[7]

[4] For a definition, see e.g., Forrester, 1994, and Checkland, 1985.

[5] As well as systems thinking, we will need to pay close attention to the human issues. Intra- and inter-generational equity is a critical aspect of each problem area individually as well as all of them together. Because we are starting from an extremely inequitable state, the necessary trade-offs and compromises will need to be made transparent. A radical improvement in global governance and consensus-building techniques will be required.

[6] "Three consumables – water, food and fuel – are perhaps the most important materials imported into urban systems" (Decker et al., 2000).

[7] Interactions between decision-makers are as important as the physical interactions. The scope of decision-maker autonomy appears to be declining. How can we achieve "joint" and "equitable" decision-making?

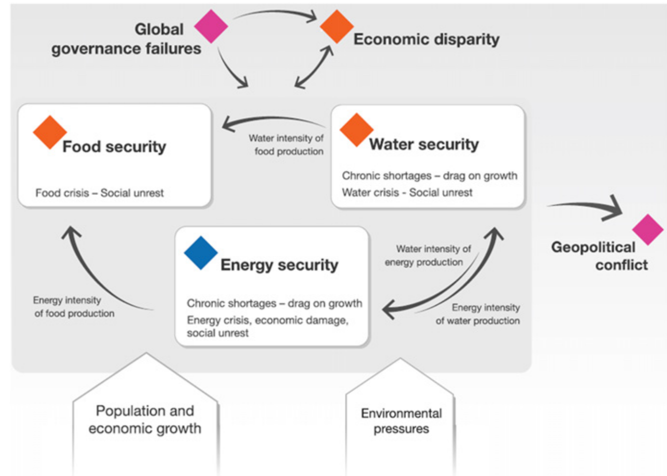

Fig. 1. Nexus schematic with a security focus (WEF, 2011b).

Some of the descriptive elements of the EWF nexus that are readily identifiable include[8]:

- All three areas have many billions of people without access (quantity or quality or both).[9]
- All have rapidly growing global demand
- All have resource constraints.
- All are "global goods" and involve international trade and have global implications.
- All have different regional availability and variations in supply and demand.
- All have strong interdependencies with climate change and the environment.
- All have deep security issues as they are fundamental to the functioning of society.
- All operate in heavily regulated markets.
- All require the explicit identification and treatment of risks.

Fig. 1 presents a schematic of the interactions with a focus on security.

It is clear that each of the three "resource spheres" affects the other in substantive ways. Ignoring effects in one can have significant impacts on another. As Lee and Ellinas (2010) note, "The anticipated bottlenecks and constraints – in energy, water and other critical natural resources and infrastructure – are bringing new political and economic challenges, as well as new and hard-to-manage instabilities." Thus, the need for a systematic, coordinated planning approach is obvious. Hussey (2010) graphically depicts the interrelationships between some energy-water interactions (with food as a "knock-on sector") using a qualitative framework (Fig. 2).

3. Sense of scale

In order to provide context and a sense of scale for our discussion, we briefly quantitatively describe some of the high-level interactions.

- A lack of access to quality services, primarily in the Least Developed Countries (LDCs), plagues all three areas.
  - 1.4 billion people without access to electricity.

[8] The World Economic Forum outlines several of these interrelated risks from government, societal and business perspectives (WEF, 2011b).

[9] Of course many of the poorest people do not have access to any of the three.

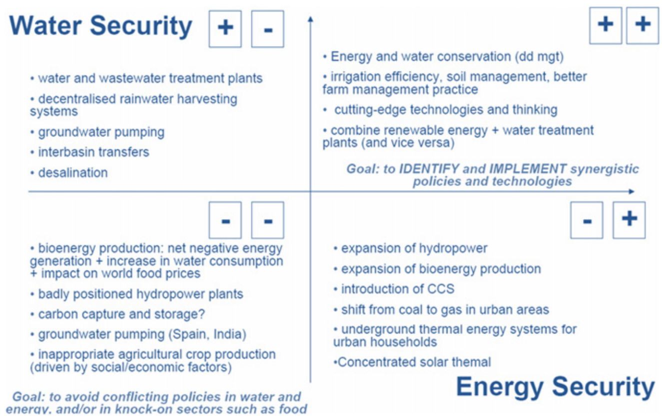

Fig. 2. Energy-Water interactions positive and negative implications (Hussey, 2010).

- ○ 3 billion without access to modern fuels or technologies for cooking/heating.
- ○ 900 million people lack access to safe water.
- ○ 2.6 billion do not have improved sanitation.
- ○ More than 900 million people are chronically hungry due to extreme poverty.
- ○ 2 billion people lack food security intermittently.

- In the power sector, thermal power plants use large amounts of water for cooling, a small amount of which is lost to evaporation (see US DOE, 2006, 2009; Macknick et al., 2011).[10] Hydropower plants use significant quantities of land[11] and interfere with existing water flows, changing silting patterns in river basins[12], and lose a considerable amount of water to evaporation (Torcelline et al., 2003). Significant quantities of water are also required for other energy processing activities, such as refining oil products or manufacturing synthetic fuels.[13]
- In the water sector, energy is used in conveyance, treatment, and distribution. About 7% of commercial energy production is used globally for managing the world's fresh water supply.[14] Before use it can be extracted, purified and distributed. After use, it can be treated and recycled; all of which requires energy.[15]
- The majority of global anthropogenic water use, in the range of 60–80%, is for irrigation (see e.g., Gerbens-Leenes et al., 2009). In arid developing countries, irrigation can account for as much as 90% of total water use.[16] For example, in India between 15–20%[17] of electricity use is attributed to irrigation.

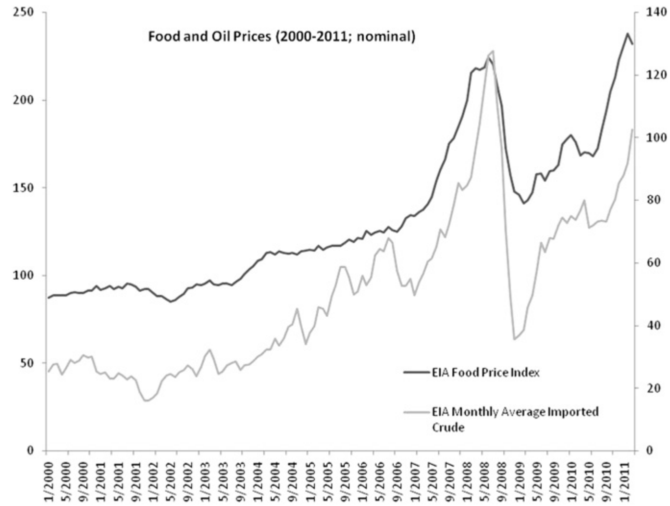

Fig. 3. Food (primary *x*-axis) and oil prices (secondary *x*-axis) 2000–2010 (FAO and EIA nominal data).

(See IEA, 2010a,b for a useful comparison of land use requirements for power generation.)

- In the food sector in OECD countries, around 3.5% of total final energy consumption is used directly in the agricultural sector (4.8% in developing countries; FAO, 2000). Additionally, food processing and transport in industrialised countries uses up to twice the energy reported solely in agriculture. For instance, in 2007, the U.S. food system accounted for almost 16% of the nation's energy use. Most of the recent increase in food-related energy use occurred in post-harvest stages (Canning, 2010).
- The close relationship between food and oil price indexes is also revealing. It generally reflects the importance of petroleum on food production through both fuel inputs (e.g., in transport and cooling facilities), and products such as fertilizer (Fig. 3).

It is clear that the interactions are both significant in scale and complexity. Creating a framework capable of abstracting the issues at appropriate levels for decision-making is a crucial step. The design of such a framework will need to be informed by detailed understanding of specific areas where the EWF nexus is apparent.

4. Examples from an energy perspective

It is very difficult to come to address the totality of all three issues without resorting to a restatement of common statistics on growth or lack of access, etc. or to somewhat diffuse guidance.[18] We briefly outline several specific areas where the EWF nexus is apparent, but currently not always benefiting from systems thinking. These are not case studies, but included as areas with distinguishable system boundaries for the EWF nexus where future, more detailed research could focus.

1. Energy access and deforestation.
2. Biofuels (and unconventional oil and gas) production.
3. Irrigation and food security.
4. Hydropower.
5. Desalinisation.

[10] Some 50% of US fresh water consumption first runs through turbines for electricity production before being piped to the end-user (USGS (U.S Geological Survey), 2004); a barrel of oil equivalent from tar sands requires three barrels of water; one kWh of coal-based electricity involves the use, on average, 95 l of water.

[11] The large land requirements of hydropower can require the relocation of activities and people. Over a million people, for example, had to be relocated because of the Three Gorges Dam Project (Chaudhuri, 2003).

[12] Damming the Nile River, for example, caused the silt – which was deposited in the yearly floods and made the Nile floodplain fertile – to be deposited behind the dam. This lowered the water storage capacity of Lake Nasser. Poor irrigation practices further waterlog soils and bring the silt to the surface.

[13] In New Mexico, for example, refineries currently use 50–180 l of water per barrel of crude oil and generate 30–120 l of wastewater (Timm, 1985).

[14] "…the water use cycle accounts for 19 percent of all electricity consumed in [California, USA] and 30% of non-power plant-related natural gas use" (CEC, 2011).

[15] For example, the energy required in California to treat wastewater for reuse ranges between 0.1 and 4.0 kWh per 1000 l (CEC (California Energy Commission), 2005).

[16] GDI (1998).

[17] Shah et al. (2004).

[18] See e.g., Wong (2010): "Holistic approaches that weigh trade-offs among the three resource systems are the future of natural resource management and, indeed, any sustainable economic or national security policy." Or see WEF (2011a,b): "The key challenge is to incorporate the complex interconnections of this nexus of risks into response strategies that are integrated and take into account the many relevant stakeholders."

- **Energy Access and deforestation:** In Uganda, as an example, limited access to electricity (only 9% of Ugandans have electricity access; IEA, 2010b) is a major drag on development, and major environmental problems include overgrazing, deforestation, and (often) low-productivity agricultural methods, all of which lead to soil erosion. 93% of the country's energy needs are supplied by wood. The resulting deforestation is a severe problem (including impacts on water systems), although its pace has slowed significantly, from a 67% loss of forests and woodlands between 1962 and 1977 to a 7.7% loss between 1983 and 1993 (see e.g., Biswas et al., 2001; Liu et al., 2008; Viswanathan and Kavi Kumar, 2005; Zahnd and Kimber, 2009). Similar problems are faced in Ethiopia. Due to its intensive exploitation, only 3% of natural forests remain intact. The government's programme to provide electricity to all citizens has put pressure on some basins. Awash Basin, as with much of the highlands of Ethiopia, has mixed crop/livestock farming in its upper reach, a mix of crop, livestock, and pastoral production in its middle section, and a nomadic pastoral system with some irrigation in its lower segment. The basin has an irrigable land area and also an important hydropower generation with a total of 110 MW at three stations, representing 14% of the national capacity. Since water availability is insufficient to meet the full needs of irrigation and power generation, the basin faces difficult tradeoffs (McCornick et al., 2008).
- **Biofuels (and unconventional oil and gas) production:** It is clear that policies to develop bioenergy alternatives to fossil fuels has often been done in the absence of a wider understanding of the full costs and benefits from multiple perspectives, including: deforestation, biodiversity, water, energy, lifecycle emissions and land use change.[19] Recent food price spikes were likely caused by many factors, including increased prices for fertilizer and fuel and thus transport, increased demand for biofuels driven by energy security and climate change concerns, as well as changing consumption patterns (see e.g., UN-Energy, 2007; Elena and Esther, 2010; Kaphengst et al., 2009; Lange, 2011; Méjean and Hope, 2010; Peters and Thielmann, 2008; Schut et al., 2010). Globally there seems to be enough land and water to grow a substantial amount of biomass for both food and bioenergy production, but not without some price impacts. However, there is an uneven distribution of natural resources, resulting in huge regional differences with important areas experiencing major land and water shortages. China and India, for example, account together for more than 35% of the total global population and both have exploited most of the land and water resources available for agriculture. On the other hand, large parts of sub-Saharan Africa and South America still have the potential, in terms of suitable land and exploitable water, to expand areas for agricultural production in addition to significant possible productivity gains for current land use (Müller et al., 2008).[20] Unconventional sources of oil and gas face similar issues. The exploitation of tar sands (Wu et al., 2009) and shale gas (Lee et al., 2011) use considerably more water than conventional oil and gas, respectively, and can cause substantial water pollution.
- **Irrigation and food security** The interrelation of energy, irrigation and food security has become a serious issue in South Africa (SA). Electricity tariffs increased by 31% from 2009 to 2010 and are planned to increase by approximately 25% for the next three consecutive years (South African Government, 2008; ESKOM, 2008). One of the areas that could be most affected by energy price increases is the agricultural sector due to its energy demand for irrigation. 25% of South Africa's staple food is grown on irrigated land. Decreasing irrigation and shifting towards rain-fed agriculture may endanger national food security especially during drought periods. South Africa has been a net food exporter from 1985 to 2008 but due to population growth and less increase in agricultural productivity in recent years, has become a food net importer.[21] As another example, Punjab has only 1.5% of India's land, but its output of rice and wheat accounts for 50% of the grain the government purchases and distributes to feed more than 400 million poor Indians. A significant problem is that farmers are pumping ('mining') aquifers faster than they can be replenished (as electricity is subsidised, this is partially due to inadequate price signals), and, as water levels drop, increased pumping is sapping an already fragile and overtaxed electricity grid. Overall, irrigation accounts for about 15–20% of India's total electricity use. One option involves the use of distributed photovoltaic powered water pumps that can introduce better pricing signals. Under appropriate conditions, PV irrigation systems are becoming utilised in this area to great success (see e.g., Sallem et al., 2009; Purohit, 2007; Hussain et al., 2010).
- **Hydropower:** Hydropower generation meets 16% of the world's electricity needs and has been one of the main driving forces behind the construction of 45,000 large dams worldwide (WCD, 2000). The generation of electricity impacts little on the quantity of water (it is limited to the loss by evaporation in the dams), but may alter the timing of stream flows, both seasonally and hourly, as the timing of water releases is generally governed by the demand curve for electricity, within environmental and engineering constraints. Conflicts can also arise between hydropower and downstream uses, including irrigation, in-stream uses, and supporting ecosystems (Briscoe, 1999). A typical case of such conflict is found in Central Asia, where the Kyrgyz Republic needs to release water in the winter time to generate electricity, while Uzbekistan and South Kazakhstan need water in the summer for their irrigation schemes (World Bank, 2004).[22] Jordan presents another

[19] In this context, the Food and Agricultural Organization of the United Nations (FAO) has established the Bioenergy and Food Security (BEFS) project to assess if and how bioenergy developments could be implemented without hindering food security (FAO, 2010). This is one of numerous complementary initiatives ongoing that focus on the broad issues of sustainability and first generation biofuels (such as the Global Bioenergy Partnership, and the International Standards Organisation (ISO)).

[20] Clearly, it is important that the energy use for biofuels production does not reach similar levels as the energy contained in the fuel, because this would make it a rather inefficient energy conversion technology instead of a source of sustainable energy. Especially for grain based ethanol production this is a concern.

[21] The evolution of energy efficiency in the food sector in recent decades provides some interesting findings (FAO, 2011a,b). Globally, energy intensity in agriculture significantly increased until the mid-1980s. From this point onwards agricultural processes have managed to produce more food per energy input. However, this global trend masks important differences between industrialised and developing countries. In real terms the energy intensity of fertilizer use and agricultural machinery has only lessened in industrialised countries, whereas it has steadily increased in developing countries since 1965 (FAO, 2011b). Reduction in food waste is another option to significantly reduce (embedded) energy. For instance, just the losses from the farm "gate to plate" would be equivalent to about 2% of total annual energy consumption in the USA (Cuellar and Weber, 2010). Roughly 30–40% of food in both the developed and developing countries is lost to waste. However the causes behind this are very different. In developing countries, food losses occur mainly onfarm, and in transport and processing stages, whilst in developed countries, most losses occur after the retail stage (Brown, 2006).

[22] However hydropower dams can also help to control flooding and store water for agricultural and other use during dry seasons. Where projects are not viable from one single perspective, multiple benefits can make a viable project. This is, for example, the case in sub-Saharan Africa, a region with ample but erratic

interesting case. The country relies on the limited water from the Jordan River and a few other river systems. Energy is needed for lifting, moving, and treating surface water, especially from the Jordan Valley. Energy imports come at significant cost, both financially and also from a foreign policy perspective (Scott et al., 2003). Energy and water pricing is another major issue. Even prior to the recent increases in energy prices, it is estimated that Jordan used 25% of its electricity, primarily generated from oil imports, to manage its limited water resources (McCornick et al., 2008).[23]

- **Desalinisation:** As an example, many island populations and large populations in the Middle East and North Africa depend on water desalination as a source of potable water and irrigation. As underground water reservoirs are rapidly depleted and population expands, it is projected that the need for desalination will rapidly rise. The dominant desalination processes: thermally driven[24] Multi Stage Flash (MSF) and reverse osmosis (RO) constitute 44% and 42% of the worldwide capacity, respectively. Thermal desalination technologies, which under the appropriate conditions can based on solar energy, rely on the distillation processes to remove fresh water from salty water. Saline feed water is heated to vaporise, causing fresh water to evaporate as steam leaving behind a highly saline solution namely, the brine. A feature of the MSF technology is that it can utilise excess thermal energy. Thus, it is possible to combine the production of large amounts of power and water in one station, thereby satisfying the demand for both of them. Energy needs for desalination are projected to grow rapidly, especially in arid regions. Water desalination in the MENA region alone is projected to grow from 8 million m^3 today to around 15 million m^3 in 2030. Depending on the country, studies project that 33–67% of power capacity additions could be combined electricity and water plant (IEA, 2005; see also: Siddiqi and Diaz, 2011; Othmer, 1975; Blanco et al., 2009; ND; Peñate and García-Rodríguez, 2011).

There are, of course, numerous other possible examples, though most still remain focused on only two dimensions of the EWF nexus. The key will likely be to draw system boundaries wide enough to encompass the enormity of the interacting vectors, while maintaining it small enough to be able to conduct useful analysis. Policy and regulatory examples that take this approach are difficult to identify readily.

5. Towards a unified framework

The challenge of understanding energy, water, and food policy interactions, and addressing them in an integrated manner, appears daunting. A vital step towards approaching the EWF nexus is to develop robust analytical tools, conceptual models,[25] appropriate and validated algorithms, and robust data sets that can supply information on the future use of energy, water and food.[26] To date, this area has been somewhat limited. This section presents a novel framework for such a support tool. First, though, it briefly alludes to the well established practices of: life cycle analysis (LCA), exergy analysis, complexity theory, operations research, material flows analysis, industrial ecology, and sustainable supply (value) chains.

There is a significant literature on the topic of LCA.[27] This ranges from product cycles to industrial processes and cleaner production to value-chain accounting. As Heller and Keoleian (2000) note, "The product life cycle system is a useful framework for studying the links between societal needs, the natural and economic processes involved in meeting these needs, and the associated environmental consequences. The ultimate goal is to guide the development of system-based solutions." These studies often consider resource sectors such as energy, water, and food, as well as the energy, water, and food inputs into products. The information can be used to improve manufacturing processes as well as regulation and policy. Likewise, the practices of exergy analysis,[28] operations research, complexity theory,[29] and industrial ecology have approached wide system boundaries that include the EWF nexus and material flows, etc. These 'methodologies' often use systems thinking and multi-criteria tools. Closely related is the concept of sustainable or 'green' value or supply chains, which considers energy, water, and food as one part of a wider production process.[30]

Historically, the seminal systems analysis study to address aspects of the EWF issues was *The Limits to Growth* in the early 1970s (Meadows et al., 1972). While providing important insights, the analysis was of less use to national policy makers. A second approach, developed around the same time to analyse the provision of energy services, focused on five connected resources: water, energy, land, materials and manpower (WELMM; Grenon and Lapillonne, 1976). However, this approach was never developed into a manageable software package that could be used by national analysts.

(*footnote continued*)
rainfall. In SSA a potential exists for many more hydropower reservoir projects that can also feed agricultural irrigation projects.

[23] Another example, the Narmada dam project in India (Wood, 2007), involves the construction of some 3200 small, medium and large dams on the Narmada river. It was estimated that the project would supply water to 30 m people and irrigate crops to feed another 20 m people. Furthermore, the dam system will irrigate a total 17,920 km2 of land. Still, the project was been under severe criticism for lack of transparency and damaging the environment. There are first signs of salinity problems and water logging along the irrigation channels build around the project (Roy, 1999). Silting of reservoirs poses a challenge as well as maintaining the huge channel system spanning several hundreds of kilometres.

[24] Thermal desalination technologies, which under the appropriate conditions can based on solar energy, rely on the distillation processes to remove fresh water from salty water. Saline feed water is heated to vaporise, causing fresh water to evaporate as steam leaving behind a highly saline solution namely, the brine. A feature of the MSF technology is that it can utilise excess thermal energy. Thus, it is possible to combine the production of large amounts of power and water in one station, thereby satisfying the demand for both of them.

[25] On the issue of conceptual models in an urban setting, Decker et al. (2000) note, "Although socioeconomic perspectives are commonly used to analyse urban dynamics, biogeochemical approaches may also be useful, in particular by advancing our understanding of cities as ecosystems. At the level of an individual organism, biogeochemistry comprises the metabolic processes: the conversion of water and food into biomass and waste. Cities transform raw materials, fuel, and water into the urban built environment, human biomass, and waste."

[26] We recognise that a "unified framework" should include the "human" aspects. Algorithms to guide policy makers will not be sufficient to establish consensus.

[27] See e.g., Abiola et al. (2010), Allen et al. (2010), Amigun et al., (2011), Azzopardi and Mutale (2010), Berkhout and Howes (1997), Byrne et al. (2007), Cerutti et al. (2010), Chaurey and Kandpal (2010), Cherubini and Strømman (2011), Dismukes et al. (2009), El-Fadel et al. (2010), Finnveden et al. (2009), Fthenakis and Kim (2010), Grossmann (2003), Hertwich et al. (1997), Ito et al. (1997), Kaldellis et al. (2009), Lee and Koh (2002), Ou et al. (2009), Perz and Bergmann (2007), Rubio Rodríguez et al. (2011), Sørensen (1994), Tan et al. (2010), Unsihuay-Vila et al. (2011), Wang et al. (2011) and Weisser (2007).

[28] Dincer (2002) notes, "From analysing the physical resource use in societies by using the concept of exergy, the inefficient and wasteful resource use will become obvious." (See also Ayres, 1996 and 1998.)

[29] See e.g., Kostlan (1988), Manson (2001), Mikulecky (2001), Nooteboom (2007), O'Sullivan (2009), Ramos-Martin (2003), Schneider and Somers (2006) and Vasileiadou and Safarzynska (2010).

[30] (See e.g., Allen and Rosselot, 1994; Ayres, 2004; Baas, 1998; Boons and Baas, 1997; Craig, 1995; Ehrenfeld, 1997; Hertwich et al., 1997; Jørgensen, 2004; Lowe and Evans, 1995; Nielsen, 2007; Ruth, 2006; Subhadra, 2011; Van Berkel et al., 1997; Wallner and Narodoslawsky, 1994; Arimura et al., 2011; Diabat and Govindan, 2011; Ferretti et al., 2007; Kainuma and Tawara, 2006; Sarkis et al., 2011; Walker et al., 2008; Wu and Pagell, 2011; Zhu et al., 2008.)

Integrated assessment models[31] vary widely in their consideration of the EWF nexus. In recent years, considerable progress has been made with regard to the interactions between energy policy and land use (Hertel et al., 2009; Rose et al., in press; Wise et al., 2009), showing that the two issues cannot be understood in isolation from one another. However, water use has yet to be integrated in any meaningful way. First attempts are underway (see e.g., Calzadilla et al., 2011; Sauer et al., 2010), but data and models are being established at the moment with actual applications still some years in the future.

The motivation for the development of this new modelling framework follows a review of existing integrated resource assessment and modelling literature.[32] This research has shown that the analysis of individual systems (such as energy or water systems) are undertaken routinely, but are often focused only on a single resource or have often been applied on an aggregated scale for use at regional or global levels and, typically, over long time periods. As Rogner (2009) notes, "…most water, energy and land-use planning, decision and policy making occurs in separate and disconnected institutional entities." Likewise, the analytical tools used to support decision-making are equally fragmented. Common tools used for energy system analysis include, for example, the MESSAGE,[33] MARKAL[34] and LEAP[35] models. A commonly used model for water system planning is the Water Evaluation and Planning system (WEAP[36]), and for water scarcity and food security planning, the Global Policy Dialogue Model (PODIUM) model is well established.[37] However, these and other models, in one way or another, lack the data and methodological components required to conduct an integrated policy assessment especially where these may be needed in a developing country policy context.[38] Generally, they focus on one resource and ignore the interconnections with other resources; have overly simplified spatial representations; are grand policy "*research*" rather than short term applied "*policy*"/decision support models, or analyse scenarios which are impractically long term.[39]

The development of the Climate, Land, Energy and Water (CLEW) modelling framework is a response to these shortcomings (IAEA (International Atomic Energy Agency), 2009,[40]). However, it is still not yet a fully integrated tool, and thus various joint side events and workshops have been held to facilitate its development.[41] Key improvements over existing approaches should include: finer geographical coverage, minimised data requirements for easy applicability in regions with limited data availability, a medium term temporal scope, multi-resource representation (including their interlinkages) and software accessible to developing country analysts. Also, it should use a systems approach, which refers to physical accounting of resources, technology and other requirements and constrains to meet certain needs and services, with the accounting extended far upstream and including externally induced effects (e.g., induced land use change).

The CLEW modelling framework in addition to mapping key relationships aims to support:

- Decision making: A well formulated integrated CLEWS tool would help decision and policy makers assess their options in terms of their likely effects on the broad CLEW system. The tool should be able to transparently evaluate the trade-offs reflected in different options.
- Policy assessments: Given limited resources, it is important for policy makers to ensure that policies are as cost-effective as possible. If multiple objectives can be achieved by a single policy, it may advance development more than policies focussed separately on single objectives.[42] A CLEWS tool should therefore provide a more complete, multi-system policy assessment.
- Facilitating policy harmonisation and integration: There are instances of very contradictory policies, e.g., electricity subsidies that accelerate aquifer depletion—that in turn lead to greater electricity use and subsidy requirements. A CLEWS tool should help harmonise potentially conflicting policies.
- Technology assessments: Some technology options can affect multiple resources, e.g., nuclear power could reduce GHG emissions, reduce the exposure to volatile fossil fuel markets, but may increase water withdrawals and use. As with other policies, a CLEWS tool should allow a more inclusive assessment of technological options.
- Scenario development: Another goal is to elaborate consistent scenarios of possible socioeconomic development trajectories with the purpose of identifying future development opportunities as well as of understanding the implications of different policies. This is important for exploring possible alternative development scenarios and the kinds of technology improvements that might significantly change development trajectories.

IAEA (International Atomic Energy Agency) (2009) shows a schematic diagram of some of the interacting issues used as inputs and parameters to a modelling exercise using the CLEWS tool (Fig. 4).

Initial results include promising quantification of the possible benefits of coherent – and negative consequences of isolated – policy at the nexus. Focusing on the Island of Mauritius, integrated CLEW modelling is used to asses a national energy security and GHG mitigation policy. Namely, the substitution of imported gasoline with domestic ethanol produced from sugar cane

[31] Tol (2006) gives a full discussion of IAMs. They are considerably wider in scope than individual sectoral models, not usually focused on security constraints, and often only focused on climate change and environmental issues.

[32] Cambridge Econometrics (2010) gives a detailed overview about a great number of modelling approaches and their options for (and current lack of) integration.

[33] MESSAGE (Model of Energy Supply Strategy Alternatives and their General Environmental Impacts) is a systems engineering optimisation model, which can be used for medium to long term energy system planning, energy policy analysis and scenario development. The model provides a framework for representing an energy system with its internal interdependencies (IIASA (International Institute for Applied Systems Analysis), 2001).

[34] Market Allocation (MARKAL) model of the ETSAP implementing agreement of the International Energy Agency (ETSAP (Energy Technologies Systems Analysis Program), 2011).

[35] Long Range Energy Alternatives Planning (LEAP) model of the Stockholm Environmental Institute (SEI (Stockhom Environment Institute), 2011).

[36] The WEAP energy model is maintained and supported by the Stockholm Environmental Institute: http://www.seib.org/software/weap.html.

[37] The Podium model is maintained and supported by the International Water Management Institute http://podium.iwmi.org/podium/.

[38] Including at sufficiently detailed scales, and with appropriate medium and long term feedbacks (e.g., climate change impacts on precipitation patterns relative to EWF planning).

[39] Examples of models which tackle some of the integrated nature of the CLEW system, but are impractical for local short-to-medium term policy making include, amongst others: MINICAM (PNL (Pacific Northwest National Laboratory), 2009), IMAGE (EMN 2011), and TIAM (Loulou and Labriet, 2008).

[40] Two full case studies using the rapidly developing CLEWS framework can be found in Rogner et al. (submitted) as well as Hermann et al. (Submitted for publication).

[41] As an example, CLEW side events have been held at the Commission for Sustainable Development (CSD) 17 (UN, 2009) and 19 (UN, 2011), and a joint ICTP–IAEA Workshop was conducted to garner inputs for refinements (ICTP (The Abdus Salam International Centre for Theoretical Physics), 2011).

[42] See, for example Howells and Laitner (2003), which shows how different industrial energy efficiency options could affect water use, employment, GHG emissions and energy investment requirements. Analyses that consider the multiple benefits of each option will yield better estimates of the overall development potential of each.

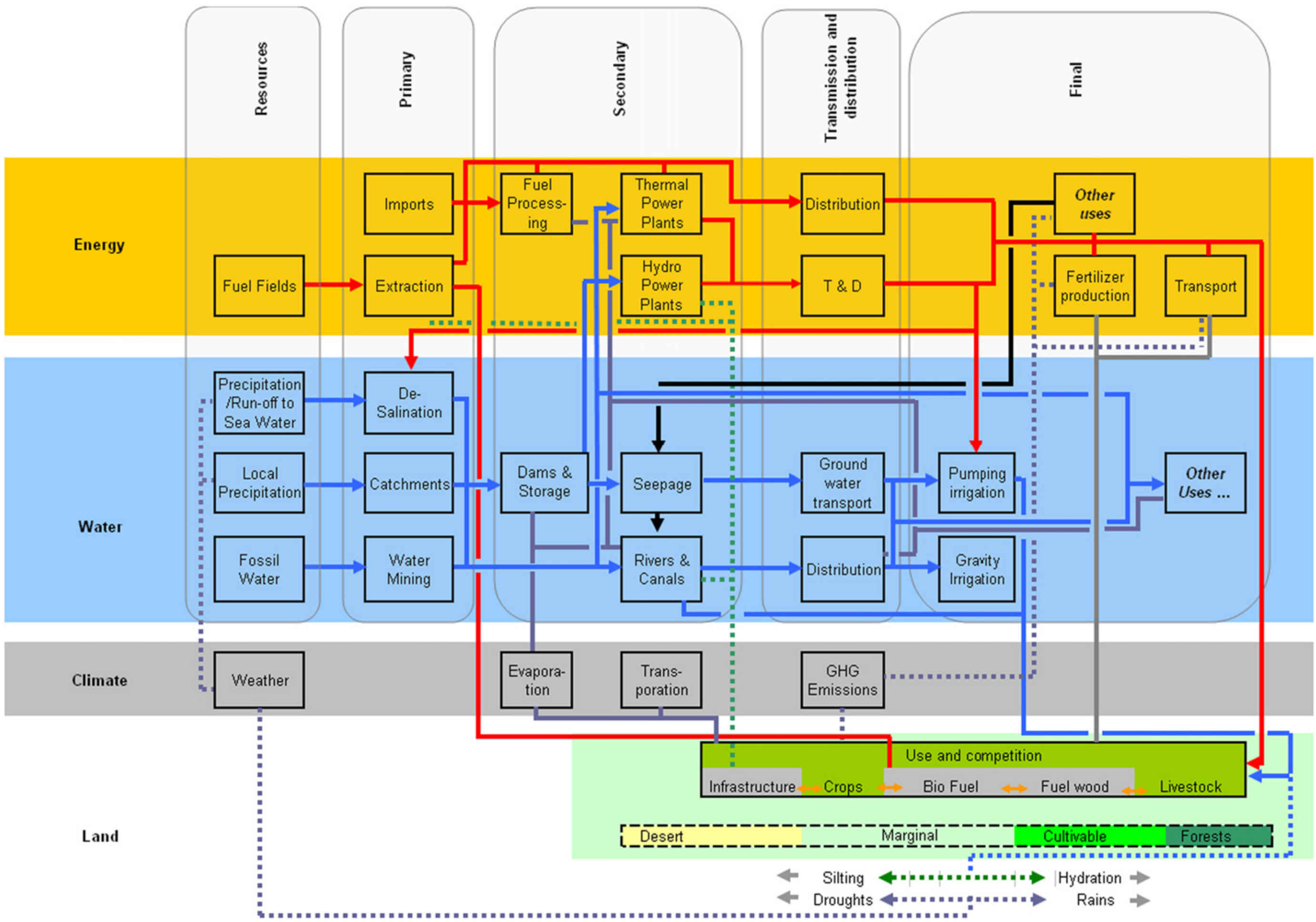

Fig. 4. Schematic of Ethanol production and energy/water/food interactions (IAEA (International Atomic Energy Agency), 2009).

(ROM, 2010). The modelling which is reported in brief by (Hermann, 2011) and in detail in (Hermann et al., submitted for publication), indicates the policy – under various assumptions – to be economically and environmentally attractive in a business as usual setting. However, as climate change may need to be adapted too, a scenario is considered where rainfall decreases (noting that seven of the last ten have been low rainfall years). The consequences of maintaining crop output are then computed in terms of water and energy needs. The result is telling; emissions increase as higher[43] volumes of water are desalinated and pumped (requiring energy) in order to help maintain the island's water balance, and to maintain crop and ethanol production levels. As a result, net emissions mitigated from introducing ethanol in the transport fleet are more than offset by increased emissions from increased coal electricity generation.[44]

6. Further work

We have alluded to three promising directions, or approaches, that may support a move towards integrated policies and programs that acknowledge and reflect these interactions. These are (1) framing the issue around strong political 'motivators' such as lack of access, rather than purely in terms of environmental impacts, (2) building institutional capacity to understand and act on the complex interactions, and (3) developing and applying modelling tools that can support integrated decision-making.

- The associated economic and security-related issues that arise from the inequalities in access to high quality services in all three areas may be a more powerful impetus from which to guide and motivate international cooperation in these areas than environmental concerns (see e.g., Bazilian et al., 2010). They also provide a sound foundation from which to formulate effective policies and regulations. The current political momentum around the EWF nexus will likely be ephemeral—embedding future actions into existing economic and security-related institutions and programmes will be essential to ensure sustainable change.
- The different vocabularies, competing priorities, institutional capabilities, and regulatory regimes between the three areas all encourage "silo thinking" in decision-making bodies. This is especially acute in the EWF area, since few people are experts on all of the areas. In some cases, this will lead to sub-optimal policy and regulatory decisions,[45] in others it will lead to large

[43] Due to recent water shortages, commercial institutions are already desalinating water for internal use, freeing up other water for uses such as irrigation.

[44] Note that the use of coal is based on an optimal cost generation electricity expansion on the Island. While low GHG emitting renewable energy may be considered as an alternative, it would be incorporated at a higher cost.

[45] Regulatory practices that encourage systems thinking will also be essential. The idea of "water exchanges", where water is traded like other commodities (wheat, corn, oil, gas, etc.) is one such notion. The price discovery that might occur in such markets will lend clear insights about the relative demand and importance

communication failures and negatively impact on development goals. The challenge is to provide decision-makers not with more information, but with better information that clarifies the trade-offs and interactions among the three issues.[46] Several organisations are taking steps to build the needed institutional capacity.[47]

- As each jurisdiction will have different levels of resource "constraints" in regards to EWF, case studies with clear system boundaries are required in order to build the evidence-base. To this end, an extension of Rogner et al. (submitted) is being undertaken that develops links between a detailed water, energy and crop production model for Mauritius (Hermann et al., submitted for publication). It tests the roles of key technologies and processes, such as ethanol production, desalination and renewable electricity generation, key policies such as food, water and energy security and does this in the context of climate change-constrained futures.

7. Conclusions

This paper briefly considered the energy, water and food nexus, primarily from a developing country perspective. It is clear that the area under consideration is vast, and that one short paper cannot hope to address the plethora of interactions and impacts in any detail. Acknowledging this, we outlined three promising areas for further exploration. It seems likely that the net outcome of treating the three areas of the EWF nexus holistically would lead to a more optimal allocation of resources, improved economic efficiency, lower environmental and health impacts and better economic development conditions, in short, overall optimisation of welfare. Although continued single sector policy making might temporarily result temporarily in an overall performance improvement of the sector concerned, it would be unlikely to persist over time. These are not new insights. However, the political timing for such messages is good.

While it is useful that there is a growing acknowledgement of the need to consider the EWF nexus holistically, the tools and expertise are not fully available to support the political dialogue.[48] Different applications of Integrated Resource Planning tools and analysis will be required to address the complexity. We must also acknowledge that undertaking the kind of inclusive policy-processes required to consider the vast array of interacting issues is difficult to transact in current government and regulatory structures and cultures—as it has been for decades. As an example, even within the energy ministries of many countries, those responsible for upstream oil and gas issues are often far removed from their colleagues working on the details of electricity market regulation, as well as those that consider water and agriculture. To actually form constructive linkages across the boundaries that exist between the three areas will require strong political leadership, compelling visions, significant cooperation and humility.

The vast gains in human welfare from improved provision of food, energy and water – and the spectre of losing this access through shortsighted policies that fail to recognise the complex interactions of these three issues – suggest that the EWF nexus must be prioritised both by the analytical policy-support community and policy-makers.

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(*footnote continued*)
between, say, food producers, upstream oil and gas exploration and processing, and power generation (see e.g., Reuters, 2011; Stern, 2010).

[46] One useful analogy is the environmental disclosure requirements that are in place in the U.S. and elsewhere. Federally-funded projects in the U.S. are required to assess and disclose their environmental impacts. This provides a basic level of information that all stakeholders can access. Similarly, one could require that a proposed policy or programme in water, energy, or food assess its impacts on the other two areas. Doing so would provide useful information to stakeholders, and would also lead to the assessing institutions developing basic analytical competence in all three areas. This type of analysis would be eased by the availability of standardized, widely accessible and easy-to-use analysis tools.

[47] Within this context, Khan (2011) noted, "Achieving water, energy and food security has thus become more urgent, and yet ever more difficult and complicated." In the financial sector, funds like the Acumen Fund (http://www.acumenfund.org) are working across all areas of the nexus to, *inter alia*, build financial capacity.

[48] The topics of energy, water and food are now often cited in the negotiations leading up to the United Nations Conference on Sustainable Development (UNCSD, informally referred to as "Rio+20"). A project entitled "Sustainable Development in the 21st century (SD21)" has been initiated to build a coherent vision of sustainable development in the 21st century. Likewise, an international conference on sustainable water, energy and food security is being hosted by the German Government in November, 2011 (Government of Germany, 2011).

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