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Alertness on various scenario of upcoming renewable energy technology systems – A Survey

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A B S T R A C T

Energy security is sometimes used to advocate renewable energy systems. Renewable energy systems can improve some aspects of security, but they will not automatically lead to the removal of all types of security problems and new problems will most certainly arise. This paper analyses energy security as- pects of renewable energy systems on the basis of a broad typology on energy and security. Renewable energy sources do not suffer from the same long-term resource availability problems as finite fossil resources and their geographical location is less concentrated, but other issues such as dependence on variable flowing resources and competition for scarce land resources will grow in importance. Many security issues related to energy are also dependent on the energy carrier rather than the energy resource and on the existence of effectively functioning institutions and regulations. New in- terdependencies will appear and will have to be handled within future international and bilateral institutional frameworks.

1. Introduction

The global energy system is dominated by fossil fuels. RE (Renewable energy)[1] currently contributes around 13% of total global primary energy supply [2] but the fraction is growing. In the EU, RE contributes around 11% of total energy [2], but its impor- tance varies significantly between member countries. For example in Sweden and Finland, RE contributed 47% and 30% of total gross final energy, respectively, in 2009, while in other countries such as the UK and the Netherlands only a few per cent of total energy was supplied by RE in that year [3]. These differences are the result of variations in geographical conditions, energy system designs and political priorities.

EU energy policy is built on three pillars: competitiveness, se- curity of supply and sustainability [4]. Although the expansion of RE is often motivated by its potential to reduce climate change, energysecurity has also been a strong driver for RE policy [5] As part of itsenergy and climate policy, the EU has issued a directive which re- quires member states to contribute to doubling RE from the 2005 level up to 20% of gross final energy consumption by 2020 [6]. In the longer term, this share could increase even more. In the scenarios developed for the EU energy roadmap [7], which envisage an emissions reduction of 80% by 2050 compared with 1990, the RE fraction varies between 55 and 75% of gross final energy consumption.[2]

The main body of literature on energy security focuses on the geopolitics and dependencies of fossil fuels (especially oil and gas), and the functionality of electricity systems. The security aspects of RE are seldom analysed and there is a significant research gap in this field [8], although there are a few reports and papers dealing with some aspects of the relationship between RE and energy se- curity (e.g. Refs. [9e11]). There are several characteristics that make RE quite different from many fossil fuels: the dependence on flows rather than exhaustible stock, the widespread location of the re- sources, the variable character of some RE electricity production technologies and the close interaction between RE and biological

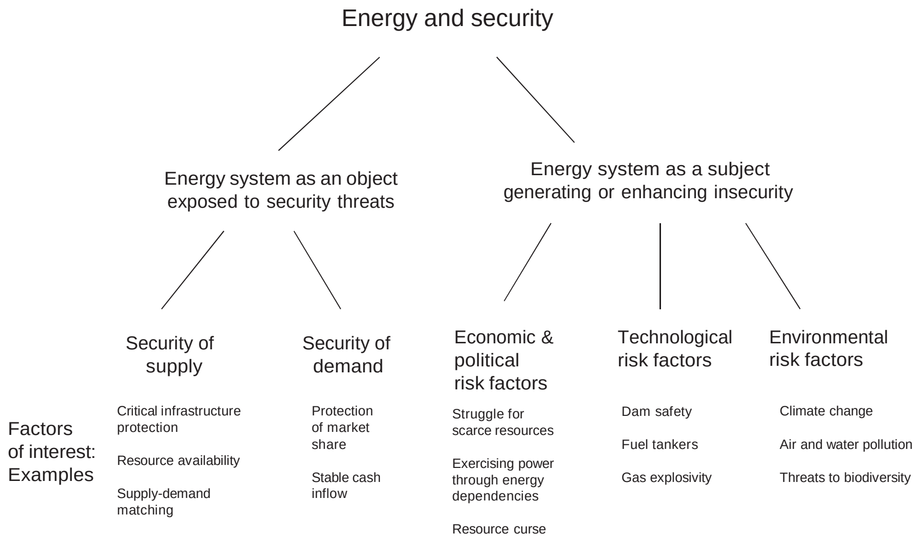

Fig. 1. The analytical structure used to study the relationships between energy and security. Based on [14].

systems (especially biomass). All this leads to security aspects that partly differ from those arising from fossil fuel-based energy systems. It is worth noting that in many studies; it is explicitly or implicitly assumed that RE is typically a domestic resource (see e.g. Refs. [7,9]), thereby reducing import dependence. Although this is largely true for the current situation, it may be quite different in the longer term if RE increases in line with the EU energy roadmap. In that case many countries will not be able to manage with local supply and will have to depend on energy imports (compare for example the discussions on the Netherlands and Germany in Refs. [12,13]).

In the following sections, the security aspects of RE are discussed following an analytical framework developed by Johansson [14]. The discussion concentrates on bioenergy, hydro power, wind power and solar energy (thermal and PV (photovoltaic)), which in most scenarios appear to be the important RE alternatives for the future. The security consequences of RE are described and compared with those of the currently dominating fossil fuels and nuclear power.

2. Relationship between energy and security

Previous studies provide a variety of definitions and approaches to energy security depending on their scope and scientific background (see e.g. Refs. [15e20]). An effort to describe the variety of perspectives was made by Ref. [14], who highlighted two approaches to energy and security that differ in principle, namely whether the energy system is an object exposed to security threats, or a subject generating or enhancing insecurity (Fig. 1). The analytical framework in Ref. [14] was developed to be applicable to any type of energy system and was chosen as basis for the analysis in this article. The structure is more inclusive than many other frameworks on energy security and encompasses a variety of security and safety issues and potential risk factors.

Within the *energy system as an object* approach, the focus lies on securing the functionality of the energy system, enabling it to provide the energy services demanded in society without major interruptions or severe price effects (see e.g. Refs. [21,22]). These aspects are usually included in the term *security of supply*. One could also choose to take the perspective of the energy supplier for which *security of demand* is essential for preserving stable income, etc. Integrating the perspectives of the consumer and supplier could be justified by their mutual, but differing, interests in an efficiently functioning energy system.

In the *security of* supply side of the approach, the focus is on the energy consumer, be it an individual, a nation or the global community. In this approach, considerations regarding long-term resource issues and short and medium-term balance between supply and demand are both of relevance, as is the adequacy and functioning of transportation, transmission and distribution infrastructure. Factors often used to qualify security of supply include resource availability, import dependency, supplier reliability, diversity in energy resources, secure transit routes, infrastructure reliability, etc. (cf. [23]).

The approach to the energy system as a *subject generating or enhancing insecurity* can in turn be divided into three different types of risk areas: *Economic-political*, *technological* and *environmental* (Fig. 1).

Economic-political risk factors arise from the competition around scarce and valuable resources, tensions, conflicts and violence resulting from overly abundant resources (the so-called resource curse), and the risk of the owner of a strategic resource using it as tool for achieving political and economic advantage. A consequence of the latter is that import dependency may appear as a negative factor in the discourse. However, liberal international relations theory presents a contrasting perspective and views interdependency as an important security-building factor (see e.g. Refs. [24,25]). According to this theory, the more dependent countries are on each other, the more secure the world will be, which will also bring security to individual countries.

Technological risk factors are associated with the physical characteristics of energy technologies, potentially leading to severe negative consequences and threats to security in cases where the system is not functioning as intended. This could be due to accidents (see e.g. Ref. [26]), hostile attacks (e.g. on hydro dams or gas or nuclear facilities)[3] or the use of radioactive material for weapon production or extortion.

Table 1
Electricity generated from renewable energy sources in 2010, globally and in the EU [2].

Renewable energy source	Electricity production 2010 world TWh	Electricity production 2010 EU TWh
Hydro power	3431	366
Biomass	331	142
Wind power	342	149
Geothermal	68	6
Solar (CSP, PV)	34	23
Other	1	1

The *environmental risk factors* category [14], includes those security threats to the environment that occur as an unintended but well-known by-product of an otherwise efficiently functioning energy system. These include environmental impacts from expected GHG (greenhouse gas) emissions (cf. [27]), threats to biodiversity from the extraction of RE sources, and health threats from air and water pollution.

Although the typology of energy and security presented in Fig. 1 can be helpful when analysing the security aspects of energy, it should be noted that it is not possible to create a firm delimitation from other policy arenas such as environmental policy and economic policy. For example, the impact of energy use on the climate is, with good reason, usually framed as an environmental or a development issue rather than a security issue [28]. The aspects analysed in this paper under a security umbrella could also be studied in terms of sustainability, cf. for example [29] who defines energy security as the “ability of an economy to provide sufficient, affordable and environmentally sustainable energy services so a to maintain maximum welfare state”.

3. Current use and future expansion of renewable energy

Today, global RE is dominated by biomass, followed by hydro energy. Wind power has boomed during recent years, but is still far behind in terms of share of total energy supply. Biomass is so far mostly used for heating purposes, in developing countries often through traditional and inefficient technologies. In industrialised countries, biomass is also used in large-scale applications (industry, district heating and electricity) that are more technically advanced in terms of both efficiency and pollution reduction. More refined fuels such as pellets and briquettes are also being developed and used. For example, the use of wood pellets in Sweden tripled between 2000 and 2010 [30]. During recent years biomass-based transportation fuels have increased rapidly in response to strong policy instruments, but still contribute only a small fraction of the consumption of biomass-based energy carriers, both globally and in the EU [2].

Renewable sources used for electricity production interact directly with fossil fuel technologies and nuclear power through the electricity grid. Globally, hydro power dominates renewable electricity production, but bioenergy and wind power also contribute significant shares of electricity production [2,31]. Solar power, produced by PV cells and thermal power plants, is growing rapidly but was in 2010 still producing less electricity than hydro, wind and bioenergy, as it is still more costly than its alternatives, at least in large-scale applications [32]. The costs for PV are, however, falling rapidly due to high learning rates [32].[4] Within the EU, renewable electricity production is dominated by the same sources as global production, although wind power and bioenergy provide a more significant share, Table 1

In scenarios which involve stringent mitigation of GHG emissions, RE grows in significance and, together with energy efficiency improvements, is the most important mitigation option in many studies (see e.g. Refs. [2,7,31]). Fossil fuels, together with CCS (carbon capture and storage) and nuclear power, are also assumed to provide significant proportions in most studies. Researchers and organisations have even developed scenarios in which all the energy demand is covered by RE [33e37].

In the frequently cited IEA (International Energy Agency) 450 ppm scenarios, RE will grow rapidly in the electricity sector to provide almost half (47%) of the global electricity supply by 2035 [2]. In the EU, the level will be even higher (56%) in that scenario. While hydro power will maintain its important role, other sources such as wind, solar and biomass power will grow much more rapidly. The use of bioenergy in most end-use sectors will also increase significantly during this period. According to the IEA 450 ppm scenario, the total global demand for bioenergy will almost double during the period 2010e2035.

For the future, two major opposing trends can be discerned. On the one hand, small-scale RE technologies, such as solar power installed in buildings, are expected to expand. At the same time, large-scale centralised solar and wind power plants are expected to be developed for economic reasons. Progress has already been made in this area. For example, the wind power turbines developed in the beginning of the 1980s often rated only about 100 kW, while those produced in recent years usually have a capacity of 1.5e 2.5 MW and are often grouped in wind power parks, with several hundred MW of output [38]. Other visionary examples are large-scale imports of solar electricity from North Africa to Europe (cf. the Desertec concept), covering between 15 and 20% of EU energy demand [39]. Although smaller in scale than fossil fuel systems, biomass technologies can also have significant advantages of scale and the use of CCS, a technology attributed to fossil fuels in the past, will become a significant option for GHG mitigation (see e.g. Ref. [40]).

Within the transportation sector, the choice of technology based on RE is less evident. Today biomass-based transportation fuels are the most important renewable alternative, and in 2010 they contributed approximately 2% of global energy used for transportation [2] (and in some areas like Brazil, the US, and the EU even [5]). Electricity and hydrogen are interesting options that could be produced from a variety of renewable energy sources but will greatly depend on the success in developing technologies such as electric or fuel cell-based vehicles. The chosen carrier will also depend on the application and the demands of the various transport modes, but biofuels, electricity and hydrogen have all appeared frequently in discussion regarding long-term solutions (see e.g. Refs. [31,41e43]).

4. Renewable energy and security aspects

Renewable energy can affect energy security in a number of ways. In this section, these effects are briefly discussed following the framework presented in Fig.1. It is not possible to explore all the various aspects involved in this short paper, but the discussion is intended to show the variety of issues worth investigating. Thorough investigations have already been carried out on some of these, whereas in other areas information on many aspects is still lacking.

4.1. Renewable energy and security of supply

In the long term (>10 years), the main advantage of RE sources from a security of supply perspective is that these energy sources are based on energy flows. In contrast, fossil fuels are based on resources that can be seen as depletable stocks, although some of the fossil resources are still very large and depletion therefore not imminent.[6] This means that with RE sources, it is possible to sustain energy supply over the long term as long as the renewable resources are utilised in a sustainable way. In the case of bioenergy this means that harvest must not exceed growth or in other ways contribute to the depletion of long-term production conditions. Although these are rather self-evident conclusions, it is less clear what conclusions can be drawn regarding feasible expansion of RE, especially as biological resources are also used for other important purposes such as food and fibre production. Existing studies report biomass potential values that vary widely [45e48].

Climate change is a factor that will have effect on energy supply although the impact and can be both positive and negative. RE sources are closely related to climate conditions and for this reason, according to [49], it can be expected that climate change will affect renewable energy sources more intensively than fossil ones. Examples of factors that will impact RE are changes in temperature, wind patterns, cloudiness and the hydrological cycle. The optimal design of future RE systems will depend on future climate and past experience of climate conditions should therefore be used with care when planning future RE systems [49e51].

In the medium term (1e10 years), the supply-demand balance will be determined by investments in adequate supply, combined with demand-reducing technologies and consumer behaviour. This fact will hold true regardless of whether investments are diverted to the fossil fuel market or the RE market. Furthermore, RE sources are often integrated within the same system (e.g. electricity or district heating system) as conventional resources, so investments in these distribution systems will support both fossil fuel and RE use. Thus, there seem to be many similarities between RE sources and fossil fuel resources in the medium term.

However, other aspects of the energy system, such as diversity and flexibility, can be important for enabling the system to cope with, or adapt to, price changes, etc. The impact of RE on diversity depends on where in the transition phase the system is. Initially, when the penetration of RE is low, diversity (in all its aspects as defined by Ref. [52]) will increase with increasing use of RE, but the diversity advantages may be reduced when the systems have become dominated by RE. In this regard, the balance between various RE sources will be important. Furthermore, the importance of diversity for reducing the vulnerability of the system to price changes will depend on how correlated prices for various energy sources are on the market (cf. [53]), and how vulnerable the study entity (country, industry, household) is to fluctuating prices. The sensitivity to future energy prices could in many cases be less pronounced for RE sources than for fossil fuels, as they often have larger upfront costs than current fossil fuel-based plants (cf. [9]). In this regard RE sources seem to be more similar to nuclear power, for which total production costs are only slightly dependent on the price of nuclear fuel [54]. Although prices for RE might follow global fossil fuel prices, the effects on a specific national economy will depend on whether the wealth transfer of rising prices stays within in the country or is transferred to exporting countries (cf. [53,55]).

[6] Sims et al. [44] estimate that the proven and probable reserves of oil and gas are enough to last for decades and in the case of coal, centuries. The abundance of the fossil resources is a potential problem from a climate change perspective.

In the short-term perspective, the most significant aspect of security of supply is the expanded use of variable electricity production, which could make it more difficult to balance supply and demand. In many aspects the variable electricity production provided by sources such as solar and wind power have similar characteristics to electricity demand, so it could be fruitful to view production as negative consumption and use similar methods to handle production and consumption variations. The development of methodologies for predicting electricity production (or negative consumption) levels will thus be very important.

There are several technical alternatives for reducing the negative aspects of variable electricity production, such as installing reserve capacity, increasing the spatial distribution of production facilities, investing in new transmission lines, investing in electricity storage units such as batteries or pumping power, or utilising storage in future electric vehicles [56e59]. The systems could gain from the rapid development of information technology and new business models (see e.g. Refs. [60,61]). However, it should be noted that smart grids could introduce new security threats, see e.g. Ref. [62]. Large fractions of variable electricity production are possible but carry some extra costs in addition to the direct costs (see e.g. Refs. [63,64]). The dependence of the new energy systems on weather conditions indicates that geographical diversification could be advantageous (see e.g. Refs. [65,66]), and thus energy independence less desirable. The smoothening of variable production will take advantage of large-scale integration of energy systems.

Security of supply is not only dependent on balances between supply and demand, but also on unexpected disturbances, technical failures, antagonistic attacks, etc. In this case, the characteristics of the technical facilities and transportation routes are determinants of the risk of disturbances, while market structures and handling strategies are important for determining how vulnerable a specific system will be. Current oil and natural gas markets are characterised by a few dominant supplying nations, a concentration that is expected to grow even more in the future (see e.g. Ref. [67]). This makes the markets vulnerable to events in these nations and also to disturbances (natural or antagonistic) to the transportation lines. With increasing fractions of RE, this dominance will probably decrease and the exposure to these countries will be reduced. Natural gas can play a role as balancing variable renewable energy production [2] and if so some of the above mentioned vulnerabilities will remain. However, the natural gas quantities required in a future EU electricity system mainly based on renewable energy, are expected to be much smaller than what is currently used for electricity production [7].

The scale of energy conversion plants (refineries, electricity production facilities, etc.) is usually larger for fossil fuel and nuclear facilities, so technical failure, for whatever reason, would have a greater impact for these than for more decentralised RE plants. However, if RE sources are dependent on concentrated facilities or transmission nodes (such as potentially from North African solar power), new vulnerabilities will be built into the systems [68].

New biofuel transportation routes will most likely develop (cf. [69]), with potential vulnerabilities. The vulnerabilities may be similar to those connected to current transports of fossil energy but may differ in magnitude and the where they will occur geographically. Exactly what a globalised future biomass market would look like and to what extent the resulting flows would be vulnerable is still an open question.

4.2. Renewable energy and security of demand

The expansion of RE at the expense of fossil fuels will have an impact on fossil fuel markets and, consequently, could have an effect on security of demand for fossil fuel-rich countries. For example, the IEA showed in recent scenarios that a climate policy which leads to efficiency improvements and diffusion of RE will reduce oil prices, which in the short run could be negative for these countries. On the other hand, with lower demand, depletion could be slowed and therefore income could be spread over a longer period. This is already a decision-making rule that is being used by some oil-producing countries [67]. It is worth noting that some of the oil-rich countries, e.g. Libya and Saudi Arabia, are also geographically located in areas in which they could become major exporters of energy carriers produced from solar energy.

Exporters of RE could develop a dependency on stable income, but it is doubtful that any country will become as dependent on energy income as current fossil fuel exporters, although this requires further investigation. Bioenergy seems to be very competitive in the former Soviet Union, East Asia, Oceania and parts of Africa [69], but due to a combination of high productivity and/or low population density, solar power and solar hydrogen production are in many studies expected to be localised in areas with large deserts or other low productivity land.

Although new important exporters of RE will appear, the importance of the sector for a nation's economy will depend on several factors. First, it is not clear how large a fraction of the final income will stay in the exporting country, depending on the relative importance of imported technology and local labour. If most of the income goes to external industries, the importance of the technology for the local economy might be rather low. Second, the possibility for any country to tap income from the system will depend on the power relations between nations. Third, the net income available for tapping will also depend on the relationship between extraction costs and energy prices. One reason for the large amounts of income in some Middle Eastern countries is the large discrepancy between production costs (less than 20 USD/barrel) and market prices (75-100 USD/barrel).

4.3. Renewable energy and economic and political risk factors

In general, RE sources are less concentrated and, to a greater or lesser degree, available in all countries. This is an argument for assuming a reduced risk of single countries being able to exert pressure or influence on individual countries or groups of countries in the way countries such as Russia are reported to do regarding gas (see e.g. Refs. [70,71]) In many studies, energy independence is credited with improving security, and for EU countries energy independence is expected to increase in systems with large fractions of RE [7]. Border conflicts generated around valuable energy resources would probably also be reduced, as a system mainly based on RE is less dependent on concentrated resources, with the possible exception of hydro power. The strategic importance of areas such as the MENA (Middle East-North Africa), which has historically steered the politics of countries such as the US, would in that case decrease. One further aspect is that some RE sources cannot be stored and therefore the possibilities to use these sources as a strategic tool are reduced [68,72].

Lilliestam and Ellenbeck [73] analysed the potential risks to the EU from the new interdependencies arising through large-scale imports of renewable electricity from North Africa. By comparing the relative importance of stable demand for energy to the supplier and stable supply of energy for the user, those authors showed that the EU can be vulnerable to coordinated political action from the supply countries, whereas a single country has more to lose than the EU from an action restricting the supply of solar electricity.

The risks of attacks by non-state actors on renewable electricity production plants and transmission have been analysed by Ref. [68], who argue that the vulnerability of power plants to attacks varies among technologies. For example, offshore wind energy and PV technologies seem to be less vulnerable than onshore wind energy and concentrated solar power. For electricity grids [68], distinguish between physical and virtual attacks and conclude that attacks on energy infrastructure by non-state actors cannot be dismissed entirely, but would most likely remain rare and have a limited impact. Grid lines are the most vulnerable component of electricity infrastructure, but the impact of an attack would probably be short-lived [68].

The risk of tensions as a result of increasing use of RE will depend on the ownership of the new technologies, the involvement of local groupings in the development and the distribution of income (cf. [68]). There could be an improvement compared with the current fossil fuel systems, since the smaller scale of renewable technologies would enable a wider group of local investors to enter the market. On the other hand, conflicts have already been reported in relation to the biofuel market, where large-scale plantations are growing in importance at the expense of small-scale farmers and local communities [74,75]. Similar conflicts have been identified for industrial tree plantations in general [76]. Land-grabbing has become a catch-all term for the current explosion of (trans)national commercial land transactions [77], which are connected not only to biofuel use, but also to diversion of food products for domestic consumption to export. Conflicts over land use are common and several land-reform activists have been murdered [74]. On the other hand, the demand for biofuels provides the producing countries with new income that can possibly be used to support economic development.

The increasing production of biomass for energy could reduce the land available for food production and thus pose a threat to food security (see e.g. Refs. [78,79]). The conflict between various uses of land, and thus the future availability of land for bioenergy, will depend on factors such as improvements in crop productivity and future diets [45,80]. Increased demand for bioenergy could lead to increasing food prices (see e.g. Refs. [81,82]), which in turn could lead to threats to food security for poor groups that do not benefit from the increasing prices. This may lead to diverging effects for different population groups within one and the same country, whereby owners of land may gain from increasing prices whereas consumers lose (see e.g. Ref. [80]). This could lead to increasing tensions among those groups, potentially leading to new conflicts.

A new area of interest is the growing demand for scarce materials for use in key systems for utilising RE, such as tellurium, ruthenium and indium for solar energy, lithium for batteries for electric vehicles, platinum for fuel cell vehicles and neodymium more recently expanding in modern wind power plants (see e.g. Refs. [8,83]). Many of these resources are concentrated to a few countries and have been highlighted as potential reasons for conflict. However, although these resources can be very valuable, the level of dependency varies and future dependency will depend on the availability of substitutes. Some of these materials could be substituted for by other, more abundant resources, but this may come at an economic cost. The long-term supply of these metals will also depend on the development of efficient recycling systems.

4.4. Renewable energy systems and technological risk factors

Examples of important technological risk factors with current fossil fuel systems are oil tanker accidents or accidents during oil extraction (for example The Deepwater Horizon event in 2010). The RE source with the greatest technological risks is probably hydro power, where dam safety is a significant issue. The energy amounts stored in hydro dams are significant and could have a severe negative impact if damaged. However, accidental dam failure rates have decreased significantly over time due to a combined effect of technological improvements and more stringent regulations [26].

In some scenarios hydrogen plays a central role for deployment of [7], especially as an energy carrier produced from solar or wind energy, harvesting the advantages that it provides in handling variable electricity production (see e.g. Ref. [33]) and reducing the cost of transportation of energy from distant areas. However, hydrogen is explosive and thus poses an accident risk and a potential target for hostile attacks. There is a vast body of literature on safety issues associated with hydrogen and security and it is quite clear that hydrogen systems will create new risks that will have to be managed (see e.g. Refs. [84,85]).

4.5. *Renewable energy and environmental risk factors*

The environmental consequences of RE have been discussed in depth in a vast number of studies and will only be touched upon briefly here. Climate change and security has been a growing research field during the past decade, with studies focussing on national and human security (see e.g. Refs. [27,86]). Renewable energy will generally lead to a reduced impact in terms of climate change compared with fossil fuels as long as it is sustainably produced. Bioenergy produced in the wrong places and with inappropriate methods may, however, lead to some or all of the advantages of RE being lost. Indirect effects may also appear if arable land used for food production is transferred to energy production. This might mean that food production moves to other areas, leading to a chain reaction resulting in more intensive agriculture elsewhere, threats to areas with great biodiversity and potential loss of carbon to the atmosphere, which would outweigh some of the positive effects of fossil fuel substitution by biomass (see e.g. Refs. [87,88]). The overall effects will depend on the incentives for improvements of productivity, developments on other markets such as those for food and fibre and the possibility to use degraded land for marginal production increases instead of forest land.

Renewable energy sources, with the exception of biomass, will not only lead to reduced emissions of CO_2 compared with fossil fuels, but also to reductions in other air pollutants such as particulate matter, sulphur, nitrogen oxides and VOCs (volatile organic compounds). In contrast, traditional use of biomass is a major source of pollution in developing countries and also locally in some industrialised countries such as Sweden. The energy carrier and combustion technology used are key factors determining the actual impact on air pollution from using biomass for RE production.

Potential negative impacts of increased use of bioenergy on ecosystems have been highlighted during recent years (see e.g. Ref. [89]), as well potential stress on water resources, as many bioenergy production systems are based on irrigation. The impact on biodiversity will depend on the scale of biomass exploitation and the methodologies used for biomass extraction. Estimates of water footprints for various energy sources show that biomass requires significantly more water than fossil fuels or than other RE sources such as wind and solar [90]. Already today water resources are scarce and with an expansion of bioenergy there would have to be an increased focus on water conservation.

5. Concluding discussion

The above discussion shows that RE will affect security and societal resilience in various ways. The impact will depend on the type of energy resource, the system design and the institutions and regulations surrounding the technology. This paper was of an explorative nature, so it was not possible to map the exact consequences of a change to RE and their magnitude. However, the sorts of security problems that may have to be addressed in a future with a larger share of RE are presented. Some of these problems may be handled within current governance frameworks, whereas others may require the development of new governance approaches.

The main advantage of RE from a long-term energy security perspective is the fact that it is based on flows instead of exhaustible stocks. This aspect is less important in the near-term, as there are still significant resources of fossil fuels available, but it will grow in importance over-time. Furthermore, the exploitation rate of the renewable resources is not unlimited and especially for biomass there are important restrictions emanating from the need to preserve long-term productivity and biodiversity as well as by competing demands.

In general, having more RE in the system can increase its diversity, making it less sensitive to some types of disturbances. This increase in diversity is relevant with regard to energy source and supplier. Due to the fact that all countries possess some renewable resources, the development of RE could secure at least some energy supply even if the global system is under severe strain. However, for economic and geographical reasons, many countries will base at least parts of their use of renewable energy on imports which could lead to new interdependencies.

Energy independence is often highlighted as a target in itself. However, dependence on a single local supplier could be as sensitive as dependence on a broader regional or global market. This is especially true for RE resources which depend on long-term climate and short-term weather patterns. Increasing use of variable electricity would be helped by electricity system integration, as this would enable the geographical variability of wind and sun to be exploited. An ever-increasing fractions of RE in the system could also affect institutional conditions. New technologies could gain from or even require reformed pricing systems, affecting both demand and supply in response to an increasingly fluctuating supply (see e.g. Refs. [91e93]). Furthermore, on a more general level energy *independence* may provide less security than *interdependencies* between states.

For RE and also for conventional systems, there will always be a trade-off between security and economic efficiency. Security of supply can usually be improved by having excess transmission and distribution capacity and reserve production plants in district heating systems and by investing in supplementary energy systems such as combined heating systems for buildings and flexible fuel vehicles.

Streamlining and adapting renewable energy carriers to the current fossil fuel-based systems is a feasible strategy for expanding RE, but as a consequence will make RE markets dependent on parallel fossil fuel markets. Although the price of locally produced renewable energy cannot be sheltered from developments on the global energy market, the local economy could be less sensitive as the extra costs for energy consumers in the area could at least partly be balanced by larger income streams. Furthermore, renewable energy will be at least as dependent on efficiently functioning technological systems as conventional energy, especially as RE is seen as especially well-suited for electricity production in many scenarios (see e.g. Ref. [7]).

The income aspect could be of interest when discussing the advantages and disadvantages of importing biomass from developing countries and the potential conflict with food security. Although the price of food products and land may rise owing to increasing demand for biofuels, all other things being equal this will also give rise to new income for the population. As an ultimate end, it is perhaps not advisable to keep food prices low, as this may encourage low efficiency in the food system, leading to higher

[7] Hydrogen is, however, not per se based on renewable energy but could be produced from fossil fuels or nuclear power as well.

demand for agricultural land and increased strain on ecosystems. Instead, it could be more important to create adequate institutions that ensure that populations are provided with resources to buy food and other necessities.

Institutions will also be essential to prevent biofuels having negative effects on biodiversity and long-term production conditions. These effects are site-specific and are probably best governed on a local basis. However, the necessary local regulations will have to be connected to global governance systems, since the consequences are global, and it might be justifiable to redirect some of the costs for the restrictions occurring in developing countries to developed countries.

Although RE can improve energy diversity in the short term, it seems that it is mostly the lower impact on climate change and the longer-term need to depend on flowing resources that will drive the change to renewable resources. For economic reasons and to minimise the potential stress on biological resources, it will be essential to use natural resources efficiently. Therefore, energy efficiency measures will be as important in systems heavily reliant on RE as in current systems dominated by fossil fuels.

The typology used in this study (Fig. 1) proved useful for mapping the various security aspects of RE but, as with most frameworks and typologies, there are difficulties in categorising complex issues under a certain label. For example, terrorist attacks on energy facilities could be seen as a security of supply issue if the focus is on the negative impact on the energy market; as a technological risk factor if the focus is mainly on the physical threats (e.g. from an attack on a hydro dam); or as an economic-political risk factor if the intention of the attackers is mainly to create economic or political damage. Similarly, the complex field of food security fits well into the economic-political risk category if the issue is seen mainly as an economic problem, for example that poor groups cannot afford rising food prices. Threats to food security that are mainly viewed as a result of land degradation and negative impacts of climate change would better fit into the environmental risk category, however. Bearing these ambiguities in mind, the typology presented here can still help structure the security aspects of RE in a useful way.

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