Energy efficiency and renewable energy in a decarbonized electric power system

P.J.S. (Hans-Paul) Siderius
Netherlands Enterprise Agency
Croeselaan 15
P.O. Box 8242
NL-3503 RE Utrecht
The Netherlands
hans-paul.siderius@rvo.nl

Keywords

renewable energy, electric power system, decarbonisation

Abstract

For long time energy efficiency and renewable energy have been treated separately, but the need to decarbonize the (electric) power system brings them together. In a decarbonized power system, any demand must be met in a sustainable, zero-carbon way. Therefore, the relation could be simply formulated as follows: energy efficiency is about reducing demand so that this can be met by electricity generated by renewable energy sources. However, competing claims from the two sides arise. The renewables claim that with the abundant availability of renewable energy there is less or no need to focus on energy efficiency. On the other hand, energy efficiency claims that it is the "first fuel" that is much cheaper than renewable energy (or any other energy source) and therefore should get priority. It seems that both claims are rooted in the current situation in which the power system in most countries is still highly carbonized and centralized, and efficiency is deployed in a modest way only. This paper provides a framework to explore relations between energy efficiency and renewables in the electric power system. The elements of the system – generation, connection, storage, control and efficiency – are in competition with each other. Different system designs will put emphasis on different elements; however, simple, single focused solutions will not realize a decarbonized power system. By looking at the extreme situation – an electric power system with renewable generation only – the consequences for energy efficiency will become clearly visible.

Introduction

For long time energy efficiency and renewable energy have been treated separately, but the need to decarbonize the electric power system brings them together. In a decarbonized power system, any demand must be met in a sustainable, zero-carbon, way. Therefore, simply said: energy efficiency is about reducing demand so that this can be met by electricity generated by renewable energy sources. However, competing claims arise. On one hand with the abundant availability of renewable energy, e.g. through photovoltaics, there would be less or no need to focus on efficiency. On the other hand, energy efficiency claims that it is the "first fuel" that is much cheaper than renewable energy (or any other energy source) and therefore should get priority. However, it seems that these claims have their roots in the current situation in which the power system in most countries is still highly carbonized and centralized, and efficiency is deployed in a modest way only.

This paper aims to sketch a framework and explore the relations between energy efficiency and renewable energy in a decarbonized electric power system. Such a framework is useful in several ways. First it can show the relations between energy efficiency and renewable energy and how these might change on the way to the decarbonization of the power system. Second it allows for different scenarios for achieving a decarbonized electric power system. Third it provides questions to guide further policy research.

In this paper we focus on the use of variable renewable energy (VRE) for generating electricity. Why pay special attention to VRE as generation source? The two main reasons are the variable character and the possibility of decentralized deployment of VRE sources, especially photovoltaics. Both issues have profound implications for both the technical and the eco-

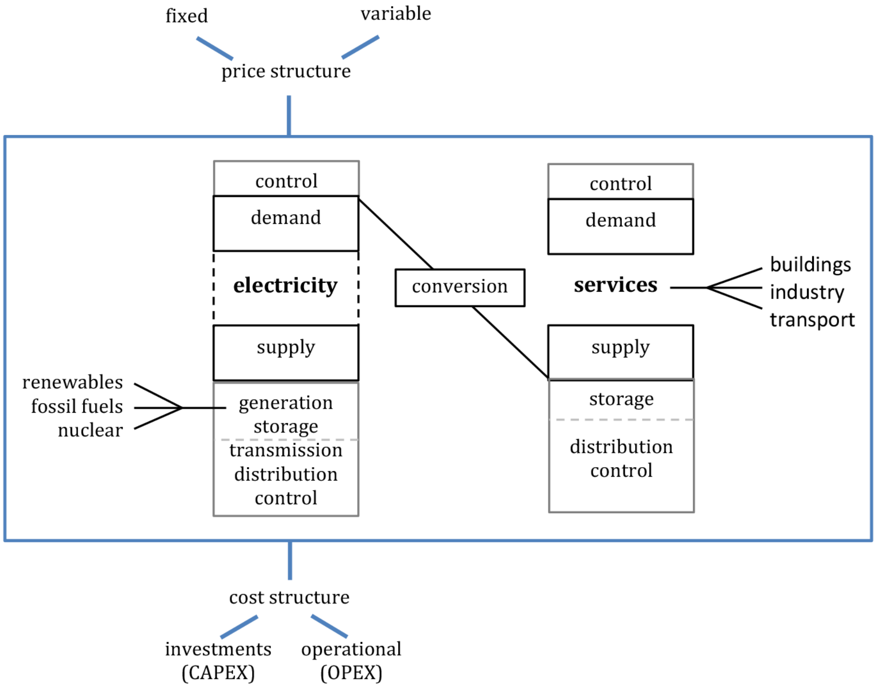

Figure 1. Technical-economic framework for the electric power sector.

nomic aspects of the electric power system. A reason to focus on electricity (generation) within the broader energy system is the trend of electrification. Although other energy carriers can be used to produce most of the energy services for industry, buildings and transport, the route to produce these carriers in a sustainable, carbon-free way runs for wind, solar and hydro via electricity. Direct use of electricity avoids the losses that go with conversion from electricity to other energy carriers, e.g. hydrogen. Also, electricity is a versatile energy carrier: it can be used to provide all basic energy carriers, whereas none of the other carriers can produce processing and light[1]. Furthermore, the direct use of electricity to provide the energy service might be more efficient than the use of other carriers. For example: an electric car is more than twice as efficient compared to a car running on gasoline or diesel (IRENA 2014).

The structure of the paper is as follows. The first section develops a framework for the analysis, providing a high-level overview of an electric power system and the criteria that guide various design aspects. The second section explores the main elements of the framework and the relations between them. The final section explicitly addresses the relation between energy efficiency and renewables and contains conclusions and recommendations for policy research.

A technical-economic framework

OVERVIEW

Energy is used in technical systems, e.g. products, installations and infrastructures to produce energy services in various sectors, e.g. (residential and commercial) buildings, industry and transport. Basic energy services are generating heat, cold, light, mechanical action, and data processing. Figure 1 shows a simplified technical-economic framework for the electric power sector.

From a demand and supply perspective, the logical order is from right to left: the demand for an energy service triggers the supply of this service, which in turn through the conversion process triggers the demand of energy that then must be supplied. Some energy services, heat, cold and mechanical action, can be stored but others, light and processing, not[2]. The supply of energy services generates a demand for energy unless the demand is supplied from storage. Thus, storage of services can decouple the demand for energy services from the demand for energy. The demand for energy must be supplied either by generation or by stored energy. Furthermore, both the demand for services and energy can be subject to control, e.g. to shift the timing of the demand. This paper focuses on the electric power system; the energy that is in demand and must be supplied is electrical energy, electricity.

The generation of electricity can be done by renewables, fossil fuels and nuclear energy. Most electricity is not generated where it is used; it must be transported and distributed. All of these elements – generation, storage, transmission, distribution and control – determine the cost structure of the supply. The cost structure can be split into investment costs (CAPEX) and operational costs (OPEX). On the long run, these costs at least must be balanced by revenues on the demand side. The price or tariff structure for the demand is based on fixed and variable components and is further influenced by e.g. taxes and subsidies. Both the technical design and the market de-

1. In principle light can be generated by every carrier that can burn, e.g. a candle or gas, but today this is not considered a suitable way for generating larger amounts of light, especially not indoors.

2. Note the storage of mechanical action, e.g. in a flywheel, is in practice much more limited than the storage of heat and cold. Furthermore, note that apart from storage losses, a small amount of energy for control purposes is needed for storage.

sign and the regulatory design are important to ensure that the power system meets several types of criteria: environmental, security of supply, costs and others, e.g. safety, job creation; see Figure 2. The technical design is mostly focused on security of supply and safety. The reason for the technical focus on (short term) security of supply is the basic characteristic of the electric power system that at any point in time supply must match demand in order to have a stable system, i.e. to be able to supply electricity at all. Not only the technical design, but also to a large extent the market design and regulatory design have to take this into account.

The criteria mentioned in Figure 2, especially in light of the transition to a decarbonized power system have been elaborated upon in various IEA publications:

- Re-powering Markets (IEA 2016), Chapter 4 (Reliability, adequacy and scarcity pricing)
- The Power of Transformation; Wind, Sun and the Economics of Flexible Power Systems (IEA 2014)
- Securing Power during the Transition; Generation Investment and Operation Issues in Electricity Markets with Low-Carbon Policies (IEA 2012)
- Harnessing Variable Renewables; A Guide to the Balancing Challenge (IEA 2011)

A central issue in these publications is how the variability of specific renewable energy sources, i.e. wind and sun, can be dealt with in the electric power system. One way of looking at this issue is to view these renewable energy sources as a special kind of generation and to answer the question how much wind and sun the electric power system can absorb (IEA 2014). In this view variable renewable energy sources are seen as "the problem" and the solution lies with the other elements of the system. Another view would be to turn this around and answer the question how the electric power system can be decarbonized with the help of – amongst others – wind and sun. In this view decarbonization is the (main) goal and all elements of the electric power system must work together to achieve this.

ENERGY EFFICIENCY AND RENEWABLE ENERGY

Where do energy efficiency and renewable energy fit in the framework of Figure 1?

Energy efficiency comes in at the conversion between the supply of an energy service and the demand of energy: it is a characteristic of a technical system and can be defined as the amount of energy services supplied per unit of energy. A technical system, e.g. a water heater, is more efficient when it produces more energy services (in this case hot water) for the same amount of energy, or when it uses less energy for producing the same amount of services. However, the concept of energy efficiency can also be used for generation, transmission and distribution and storage. A generator is more efficient if it generates more output (kWh) with the same input, whether fossil fuels, solar or wind. A transmission line (for electricity) is more efficient if it transports a certain amount of electricity with lower losses. A storage system is more efficient if the losses of storage and retrieval for one unit of energy are lower. Control can influence energy efficiency in an indirect way by creating more favourable conditions for the technical system.

The impact of energy efficiency – through the technical system – on the electric power system is dependent on the use of the technical system, both the time of use and the amount of energy services delivered. When a product is not used, its energy efficiency does not affect the electric power system at all, i.e. it does not matter whether the efficiency is high or low.

Renewable energy is a generic term for renewable energy sources, e.g. hydro, wind, solar, waves, biomass and geothermal, that can be used to generate electricity. Note that, as shown in Figure 1, renewable energy also can be used to "directly" (by means of a technical system) generate energy services, especially heat, e.g. by means of a solar water heater. Cold, light and mechanical action can in principle also be generated but this is less practical or common.

Wind and solar are variable renewable energy (VRE; see IEA 2014) sources where the variability refers to the availability of these sources to generate electricity. More specifically, contrary to fossil fuels but also to geothermal or hydro energy sources, there is – given a certain location – no human control over the

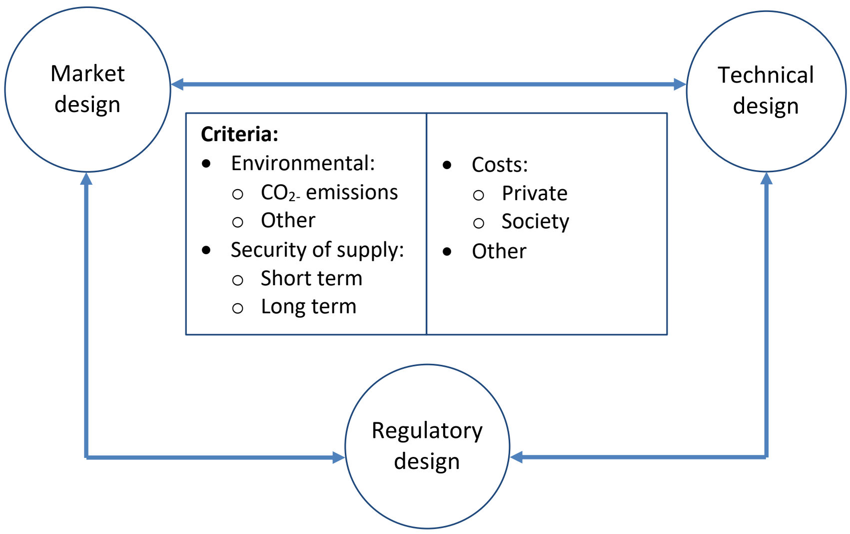

Figure 2. Design aspects and criteria for the electric power system.

availability of wind or solar. However, their availability can be predicted, albeit with some uncertainty.

There is one aspect where other energy carriers have an advantage over electricity and that is storage. Whereas all fossil fuels including hydrogen produced by electricity are storable by themselves, electricity is not. Apart from storage in capacitors, electricity can only be stored by conversion to another form of energy, e.g. chemical energy in a battery or kinetic energy in a flywheel.

Both renewable energy and energy efficiency can be used to reduce the use of fossil fuels and thereby to decarbonize the electric power system. Renewable energy can generate electricity without using fossil fuels and energy efficiency can reduce the amount of energy needed (for delivering the same amount of service). Within the framework of a decarbonized electric power system, still a large number of options exist. The choices made will depend amongst others on the cost of the generation of electricity, transmission and distribution, storage, control and energy efficiency. Note that these elements are interdependent and that many factors influence the costs of these options and other criteria indicated in Figure 2.

Exploring elements of the framework

In this section we explore the main elements of the framework shown in Figure 1 and Figure 2. We start with the core of the electric power system: matching demand and supply, including generation, transmission and distribution, storage and control. Then we deal with the price structure, the cost structure, and the market design and regulatory framework. For each of these elements we indicate the impact of increasing deployment of VRE sources and energy efficiency.

MATCHING DEMAND AND SUPPLY

In the electric power system supply must equal demand at all times to provide a stable system. Compared to a conventional electric power system with a limited amount of VRE, in a decarbonized power system with large shares of VRE sources not only the demand but especially the generation has a higher variability. In order to match demand and supply, this variability – of both demand and supply – needs to be managed; which includes more options than only reducing variability of demand or supply. The variability of the demand (of electricity) can be managed by demand-side control, via the demand and supply of energy services and storage of energy services, especially heat and cold. The variability of supply can be reduced/managed by storage (reducing temporal variability) and transmission lines (reducing geographical variability) (IEA 2011, p. 35–36).

Matching demand and supply in light of the variability of VRE generation is not only a challenge when the demand is high and VRE generation is low, but also when the demand is low and VRE generation is high. In general, this means that flexibility of VRE generators is needed in both ways, up and down. Moreover, VRE generation increases the uncertainty of generation. Although forecasts of VRE generation have become more accurate, especially within short(er) time horizons (Andrade and Bessa 2017) still forecast errors are generally higher compared to a conventional power system. The main consequence of the variability of VRE generation for energy efficiency lies in the economic assessment. The value of a kWh saved for the system depends upon the moment; when VRE generation is high and demand is low, this value might even be negative.

Balancing (merit order)

In a conventional power system balancing is about dispatching the right generator at the right moment. What is "right" is decided with the help of a merit order curve that ranks available generators based on ascending order of price (which may reflect the order of their short-run marginal costs of production) together with the amount of energy that will be supplied. In a centralized managed power system those generators with the lowest marginal costs are the first ones to be brought online to meet demand, and the generators with the highest marginal costs are the last to be brought online. In this situation quickly dispatchable generators (and demand response) provide flexibility. Balancing can be done at different levels of the power system. Whereas in conventional power systems balancing refers to the transmission grid level because there most of the generation is located, VRE sources are also located at the distribution level and the local level.

The impact of energy efficiency on the merit order is as follows: improving energy efficiency will decrease the total demand and if this decrease is substantial the generator(s) with the highest marginal costs (to the right in the merit order curve) will not/never be brought online. However, the structure of the merit order will not change.

The impact of increased deployment of renewable energy sources on the merit order is different. The merit order itself will become much more variable over time. When the wind blows and the sun shines (in a certain region), VRE sources will enter the merit-order curve somewhere at the left because their marginal costs are low. Depending on the amount of electricity generated they will push out more costly generators up to the point that also the conventional base load generators are switched off – and all demand can be met by VRE sources. Note that the time dimension is important: VRE sources can only replace base load when their output can be guaranteed over a certain period to be at least the minimum output that a one or more base load generators can deliver. Therefore, VRE sources sometimes need to be switched off or curtailed to avoid switching off base load generators that would need to be brought online again within the period that is technically feasible.

Resource adequacy

Resource adequacy relates to the electric power system being able to meet peak demand. In a conventional power system this means that enough generation capacity needs to be available to meet peak demand (plus some margin). In a decarbonized system all resources (power plants, demand side flexibility, storage and interconnection) can be used to meet peak demand. Furthermore, since resource adequacy includes a strong forward-looking component, energy efficiency is also a resource. If demand can be stabilized or decreased by means of energy efficiency measures, then there is no or less need for investment in other resources. Like building extra generating capacity, storage, control or interconnection, energy efficiency is an investment that can have a long lead-time between planning and being operational.

GENERATION, TRANSMISSION AND DISTRIBUTION, STORAGE, CONTROL AND ENERGY EFFICIENCY

Generation, transmission and distribution (interconnection), storage, control and energy efficiency (of technical systems) are the technical elements of an electric power system. Together they provide a large range of design flexibility for power systems. This section very briefly sketches these technical elements and their relations, indicating their role in a decarbonized power system.

Generation

An overview of generation techniques for generation technologies and systems can be found in EUREL (2012, chapter 7). This paper focuses on VRE sources for generating electricity. Two important characteristics of VRE sources already mentioned are variability and the possibility of decentralized deployment. The main difference in variability between wind and solar is the seasonal (summer-winter) variability and especially the diurnal variability of solar. An overview of technology development for VRE sources is provided in IEA (2017).

Transmission and distribution

The transmission and distribution grids serve various functions. The main function is to connect the (point of) supply of electricity to the (point of) consumption of electricity. A physical consequence of connecting generators to the same grid is that the frequency is the same everywhere in the grid. Frequency deviations indicate differences between demand[3] and supply: in case of decreasing frequency demand exceeds supply, in case of increasing frequency supply exceeds demand. These frequency deviations are used to automatically control the generators connected to the grid and signal that more or less supply is needed.

Since the uptake of VRE sources the notion of a smart grid has become ever more relevant; see e.g. Kok et al. (2010). One of the newer functions is the ability to charge costs at any node of the grid: block chain; see PwC (2017). This technology will allow direct transactions between any supplier of electricity and any customer, e.g. it will allow to sell the electricity produced by the PV system on your roof to your neighbour.

VRE can be connected to the grid at various levels. Moreover, often geographical imbalance exists between the location of the connection (feed-in) of VRE sources and the location of the demand, e.g. in Germany where wind generates power in the North, whereas demand gravitates towards the South. Therefore, in general the uptake of VRE is assumed to go hand in hand with reinforcements of distribution and transmission grids. However, both storage and demand-side control can replace grid reinforcements to a certain extent; see Agora (2017) for Germany.

Storage

In Figure 1 storage is depicted as a supply source for electricity and services. Although the filling of the storage can be a demand, in the end the (main) aim of storage is to decouple (in time) generation and supply, or said otherwise to supply electricity without generation (at the same time). However, apart from the supply function, storage can fulfil a large number of other functions related to the electric power system, e.g. frequency regulation, voltage support, spinning reserve (Fuchs et al 2012, p. 3). Different types of storage have different characteristics, e.g. ramping, round trip efficiency, and fulfil different functions in the electric power system; see EASAC (2017). Storage of energy services is restricted to heat and cold. However, these constitute the largest energy demands. Furthermore, this type of storage enables long(er)-term (seasonal) storage. Through storage (of energy services) the link with other energy sectors can be made: sector coupling.

An electric power system largely based on VRE sources needs storage, because even when the power system covers a large area there will always be periods when there is no wind and no sun to generate electricity. Important questions are what type of storage, including other energy carriers like hydrogen, and how much storage (amount of power and duration of supply) is needed and where can it be located; see e.g. Subkankulova et al. (2017) for the UK. The latter question implies a relation between storage and interconnection: better interconnection can make VRE available over a larger area; this could result in less storage capacity needed. But also, the opposite could apply: increased local and regional storage capacity could result in less interconnection capacity needed. On the local level (e.g. a micro grid) storage can increase self-consumption of local PV generated electricity (Bruce-Konuah and Gupta 2017).

Demand-side control (demand side flexibility)

It has been acknowledged for quite some time that matching demand and supply can also be achieved by controlling the demand (Lampropoulos et al. (2013)). Demand-side control[4] means controlling the time, duration and amount of electricity used in order to a) use less when demand is high and/or b) use more when demand is low, where 'high' and 'low' are relative to the available supply or to each other in case both are applied. An example of a) is switching off the air conditioner on a hot summer afternoon to avoid peak demand; an example of b) is heating an electric storage water heater during the night. If in the air conditioner example the house would be pre-cooled before switching off the air conditioner, this is an example of a combination of b) and a).

With more VRE sources demand-side control becomes more variable in time and – when balancing principles are applied at the lowest level of the grid – also more frequent; the reason being that the output of VRE sources is more variable. If there is enough sun and wind on a hot summer afternoon there might be enough generation to supply all air conditioners, whereas on a hazy, windless afternoon there might be not.

Demand-side control and storage are to a certain extent competing measures: both decouple the energy services needed from the generation of electricity. Demand-side control decouples energy services from the demand of energy by changing the time of supplying the energy services. It uses the comfort margins of the user and the characteristics of the system, e.g.

3. Note that by definition consumption equals supply, but using the economics definition of demand (the amount of energy energy customers would buy at a certain market price were supply available), demand can exceed supply or be below supply.

4. Also called demand-side flexibility or demand-side management, where the latter could be interpreted as broader than demand-side control, e.g. including energy efficiency measures; see Lampropoulos et al. (2013).

the thermal mass of the building. Storage on the other hand decouples the generation of electricity from the supply of electricity (storage of electricity) or decouples the supply of services from the demand of energy (storage of services).

The impact of energy efficiency on demand-side control is there is less demand to be varied. This holds both for the situation when there is too little generation and for the situation where there is too much generation. However, this effect might not be that large if electricity is taking over powering the functions that now (also) are powered by gas and oil. If water and space heating is done with (electrical) heat pumps instead of gas or oil-fired combi-boilers then – no matter how efficient these will be – providing this function will add to the electricity consumption. Moreover, these functions can be very well used in demand-side control; see Gillich (2017). Note that demand-side control can affect the energy efficiency. In part load, induced by a demand-side control action, the equipment might not be as efficient as in full load. When the heating cycle of a washing machine is interrupted because of a demand-side control action, the load and the water will cool down; the heating up when resuming the washing program requires some (extra) energy.

Energy efficiency

Energy efficiency is a technical characteristic of the equipment or system. The impact of (improved) energy efficiency is that the equipment will need less electricity to provide the same level of service[5] and therefore less electricity needs to be generated. Note that the point in time that this energy will be needed depends on the (time of) use of the equipment and is not considered to be part of energy efficiency.

Improvement of energy efficiency is mainly achieved through investments in equipment (hardware and software) and operational procedures. Note that also reduction of (the amount of) energy services will in most cases result in a reduced energy consumption. If this is applied at certain points in time, it is considered part of demand-side control. If it is applied continuously, it is considered demand reduction.

Improved energy efficiency directly impacts generation, transmission and distribution, storage and control as has been indicated in the foregoing sections. The balance between the various elements of the electric power system will be influenced by (relative) costs and complexity issues (see section on market design and regulatory framework).

There is a specific issue regarding energy efficiency and PV generation. PV systems generate electricity at very low voltage DC levels. Since the electricity grid at most end-users operates at 230 V, 50 Hz the electricity generated by PV systems has to be converted to this level. However, most electronic equipment operates at very low voltage DC levels and thus requires again a conversion (mostly by the power supply in the equipment). Feeding electricity generated by PV directly into this equipment, including electric vehicle chargers, would save two conversions that each have an efficiency of around 90 %.

COST STRUCTURE

As indicated in Figure 1 the basic types of cost are investment costs and operational costs. Operational costs include fuel costs and maintenance costs. Because fuel costs for VRE are zero and maintenance costs are limited, the main costs for VRE sources are fixed costs, or said otherwise because wind and sun are for free, marginal costs of VRE sources are almost zero. As shown earlier, the consequence is that VRE sources are first in the merit-order curve – when the wind blows or the sun shines.

The variability of VRE adds other costs to the electric power system, especially storage, control systems to enable demand flexibility and (long distance) interconnectors. Almost all of these costs will be investment costs and therefore fixed, or said otherwise, sunk when done.

If this cost structure is directly mapped to the tariff structure, then the tariff will to a large extent consist of a fixed fee (flat rate). The consequence would be that for individual end-users generation and energy efficiency will not be economical because they would only affect the (small) variable component of the tariff. Storage and demand flexibility at end-users might be more worthwhile when aggregated and integrated in the larger system.

PRICE/TARIFF STRUCTURE (WHOLESALE AND RETAIL MARKET)

Revenues on the demand side must on average balance the costs, for the electric power system as a whole but in a competitive market also for individual companies. Furthermore, prices or tariffs[6] are used to influence behaviour of end-users, e.g. to use electricity produced by renewables or to use (or not use) electricity at a certain time. Since electricity is seen as a basic necessity, also political aspects come into play, e.g. tariffs for end-users can be capped and in general (average) tariffs should be at a level that is "affordable"; see e.g. the Energy Union package of the European Commission (2015).

Variable pricing is seen as a solution to manage the demand curve or more explicitly to trigger demand-side control. In a conventional system this means smoothening the demand curve – filling the valleys and clipping the peaks – in order to allow running as much (cheap) base load generation as possible. However, in a power system with a large share of VRE sources, generation itself will be variable and thus variable pricing could be an instrument to stimulate the demand to follow the generation.

An issue is how large the variability of the price can be and what the impact is on the demand. In relation to the variability of the price two aspects play a role. If the variability of the price is to reflect the variability of the costs, then the latter is important. As indicated in the section on the cost structure, the costs in a decarbonized power system might not be that variable, given that the largest share of costs are investment costs. The second aspect is how much variability in prices (for end-users) is allowed by the regulatory or political framework. If prices are

5. However, improved energy efficiency with decreased costs for energy as a consequence can also increase the demand for the service and thereby the demand for energy. This is called the rebound effect (Sorrel and Dimitropoulos 2008), and in some cases – improvement of insulation of households suffering from fuel poverty – this is a desired effect. In the literature some argue that energy efficiency does not reduce energy demand at all (see Herring 1999) but in general the rebound effect is considered to vary between a few percent and maximum 30 % (Sorrell et al. 2009).

6. The term 'prices' seems to be more used for the wholesale market, whereas the term 'tariffs' refers to the retail market.

capped to ensure affordability of electricity then this will reduce variability and therefore the steering function of prices.

Related to this is the impact of prices on demand. In general, on the short run, electricity use at end-users is fairly inelastic (Ryan et al. 2011, p. 20) which means that price changes do not influence demand that much. Furthermore, for many end-users, both household and commercial, energy costs are only a small part of their budget. A large price increase would be needed to change (i.e. lower) demand, but in many cases such an increase would not be possible for political reasons. An example of price peaks that raised political concern, were those in the Nordic wholesale market during winter 2009–2010 (NordREG 2011).

Finally, there might be other reasons why electricity retail companies do not offer variable tariffs to (all) end-users. They might want to hedge the risk themselves and ask a premium for that – which is higher than the additional costs so it will increase their profit[7]. This could be marketed as a "care free" or "flat fee" tariff.

The price in the wholesale market is determined by the merit-order curve: the price to be paid is that of the highest bid that is brought online to meet the demand. In the literature the merit order curve is used to show the merit order-effect (Cludius et al. (2013), Dillig (2016)), i.e. the effect that generators running on VRE have on the price. The effect depends on the actual demands: at lower demands the price effect may be zero because the substituted generators have almost the same marginal costs, at higher demands the price effect may be considerable because the "last" segments of the demand curve at high demands are met by generators with a high marginal cost.

In general, the literature shows that in the current power systems the integration of VRE sources decreases the price (Sensfusz et al. 2007, Paraschiv et al. 2014)[8]. In most cases the price decreases more than outweighs the price increase related to taxes to finance the VRE subsidy schemes (Sensfusz et al. 2007). As indicated, with further increase in VRE sources, investments are needed in (a combination of) storage, demand-side control, interconnection and energy efficiency. Of these storage and demand-side control can play a role in the merit-order curve; storage is a supply source and demand-side control influences the demand curve.

Investments in grid infrastructure are determined by the (maximum) capacity and not by the amount of energy transported. Payment for grid infrastructure by end-users can be a separate charge (based on capacity) or included in the electricity (kWh) price. The rationality behind the latter is that end-users who use more electricity also require more grid capacity to get this electricity to them. However, when producing and using their own electricity, the consumption from the grid and thereby the financial contribution to the grid decreases whereas the capacity required stays the same or even increases; see e.g. Jargstorf et al. (2015). Therefore, a capacity-based charge better reflects the costs. As a consequence, improvements in energy efficiency that do not affect the capacity required yield less monetary savings.

7. Note that because they do this for a large number of customers they probably will be able to do this cheaper than an individual customer.

8. Note that this effect is partly due to the regulatory framework that provides a priority dispatch for VRE sources.

Related to this topic is how on-site electricity generation is dealt with. If "net metering" is applied, total consumption on the meter for a certain period would equal total consumption for that period minus total generation in that period. This type of metering is independent from point of time of generation and consumption, meaning that electricity returned to the grid has the same monetary value as the electricity consumed. In order to avoid this, smart meters can both meter in and out flowing electricity and the price paid to the end-user for generated electricity that is fed into the grid can be (much) lower than the price for electricity consumed (and delivered by the grid). In this case it can be worthwhile for end-users to apply demand-side control or storage in order to use as much of the generated electricity themselves.

MARKET DESIGN AND REGULATORY FRAMEWORK

In general, the function of a "market" is to provide a coordination mechanism for bringing together demand and supply – regarding this paper the demand and supply of electricity – in the most optimal way, which in many cases means least (overall) costs. Note that especially in the electricity sector other coordination mechanisms, such as integrated resource planning, have been applied. With the liberalization of the electricity sector, the vertically integrated planning has been replaced by markets: energy markets, capacity markets and even transmission markets. However, this begs the question how these markets are coordinated. Currently market design issues, including regulatory aspects, mainly cover the following two topics:

- Regulation of energy markets, including: entry of VRE and other renewable energy generators (privileged access), tariff structure and tariff caps, ensuring security of system operations.
- Regulation of resource adequacy.

The market mechanism to match demand and supply focuses on meeting short-term energy (power) demands; therefore they are called "energy" markets. In the literature it is discussed whether energy markets are also suited to deal with resource adequacy (IEA 2016). As indicated resource adequacy is related to meeting peak demand, including providing reserve capacity. A characteristic of peak demand is that its power levels are only required for a relatively low number of hours per year. This means that the generation resources installed to meet peak demand in the energy market have only a limited number of hours to recover their costs. Moreover, it is uncertain whether such a peak will occur anyway (in any year), or said otherwise reserve capacity in a well-organized system will not make any hours at all. Combined with capping of market prices (also done to prevent "gaming") it is unlikely that peak generators will earn their costs back in an energy market – the so-called "missing money problem" (Papalexoloulos et al. 2015). Also, strategic reserves established for reliability reasons cannot recover their costs through the market. Therefore, in many energy-only markets, additionally capacity markets are introduced or strategic reserves are financed to ensure resource adequacy and generating resources are able to recover their (fixed) costs; see e.g. Green and Vasilakos (2011).

Regarding the relation of VRE and reliability, IEA (2016, p. 101–102) lists five reasons why reliability is challenged with the uptake of VRE of which two are relevant for this paper. The first reason deals with the variable nature of variable renewable energy. Due to this variable nature, the contribution of variable renewable energy sources to meeting peak demand is limited. Especially for solar power in Europe where peak demand is on winter evenings (light + electric heating). As indicated above, an electric power system that is largely based on VRE sources needs storage anyway to some extent. Regarding the "winter" peak it means again that demand needs to be managed and that supply, including storage, needs to be dimensioned to meet the (remaining) demand. Second reason is that VRE sources decrease the number of hours with high loads, which means that the cost per running hour for the capacity that is set up to meet these loads increases. However, in a 100 % renewable electric power system this reason no longer makes sense, since not only hours with peak demand can be critical to the system, but in principle all hours where demand is higher than supply. On the other hand, this means that all mechanisms that need to be installed in a 100 % renewable power system to deal with variability also deal with peak demand. An interesting question is whether in a decarbonized power system peak capacity is still needed. In any case specific VRE sources cannot be designated as peak generation capacity (only) because it cannot be guaranteed that the wind blows or the sun shines when their generation is needed. So peak capacity could come from storage, whether battery, hydro or through biomass or hydrogen. However, since the impact of demand-side control and storage will anyhow have to be used to avoid sharp peaks, chances are that the conventional peak would transform into a plateau (with a lower level).

Finally, we discuss two related issues regarding the market design: long term planning and coordination between the various elements of a decarbonized electric power system. Long term planning starts at looking at demand trends, including the speed in which these trends will occur. Different scenarios can e.g. be imagined for the uptake of electric vehicles or electric heat pumps; see e.g. Energy Technology Perspectives 2017 (IEA 2017) and earlier versions for a technology outlook on various energy services sectors. The demand trends will also be influenced by trends in efficiency of technologies. A next step is how the demand will be met. This requires a mix of (VRE) generation, storage, connection (transmission and distribution) and control. For the long term, at least the total amount of energy demand needs to be generated; this determines the minimum generation capacity. However, the design of the (technical) system faces several challenges. We have shown above that various elements of the electric power system are in direct relation and competition with each other. Some examples are: improving energy efficiency versus installing more VRE generation; increasing interconnection versus using storage; using demand-side control as flexibility tool versus storage as a buffer between generation and demand.

This begs the question how these choices can be made. Can this be done with help of economic or financial tools, e.g. levelized cost of electricity (LCOE), or do we need to take into account other criteria? In several discussions on the integration of VRE sources in the electric power system a plea is made for a whole system analysis or an integrated approach; see e.g. Duane (2010) and Felder (2011). What does this mean? Does it mean that we need to go back to integrated resource planning? And what is the role of markets?

Another issue is that markets and some infrastructure investments might not very well go together. Markets are about competition; this includes that participants in the market have a choice and – equally important – that they can change their choice over time. However, especially investments in infrastructure can create a challenge: for the lowest cost per end-user they require that all end-users participate for a long enough period to earn back the investment. This would mean that for that period these end-users are not allowed to change. When e.g. (energy market) competition law forbids such exclusive contracts, the investment might not be profitable and therefore not be done (at least by market parties). District heating networks are a classic example. The establishment or renovation of a district-heating network requires large investments. If energy market laws forbid e.g. contracts longer than 1 year, the return on investment can become too uncertain. On the other hand, if the price structure is made more variable (than the costs in reality are) efficiency measures taken by some end-users will profit them but will put upward pressure on prices.

Conclusions and recommendations

RENEWABLE ENERGY AND ENERGY EFFICIENCY

The foregoing sections showed that more integration of renewables in the electric power system – ultimately realizing a decarbonized power system where all electricity is being produced by (variable) renewables – will have serious consequences for energy efficiency policy.

A decarbonized electric power system requires first and foremost more *flexibility* to manage variability in generation and demand. The elements that realize flexibility are storage, demand-side control and connections (transmission and distribution). Energy efficiency as such is not flexible: it is a characteristic of a product or a technical system and e.g. independent of the time of use of the product. This means that energy efficiency alone cannot accommodate a decarbonized electric power system. Energy efficiency however is still the only factor that influences the integrated total amount of electricity needed for delivering the energy services that society wants[9].

Second, generation by VRE sources and flexibility can be realized at various levels, from the local (home) grid to the transmission grid level. This makes the electric power system (technically) more complex. In the past the centrally generated electricity was transported through the transmission and distribution grid to fulfil the demand at end-users; this demand could be reduced by energy efficiency measures. In a decarbonized electric power system, not only energy efficiency measures but also generation and the flexibility tools can be applied at all system levels; see also Schleicher-Tappeser (2012, p. 73).

The flexibility and especially the complexity are not only a technical issue but also a policy challenge. The policy aim as given by the Paris agreement is to realize a decarbonized elec-

9. Several scenarios, e.g. Lechtenböhmer et al. (2017), indicate that we drastically need to reduce the total amount of electricity needed to enable the decarbonized supply of it.

tric power system before 2050 at lowest (overall) costs[10]. The paradox of complexity for policy can be sketched as follows. On one hand the complexity asks for overall cost minimization. However, this might run against some of the liberalization in the electricity sector, which in turn might go against the overall cost minimization goal. Or said otherwise, in order to deal with the system complexity, the system might need to be broken down in different parts that individually are easier to optimize but where there is less control over the overall optimization between these parts. Furthermore, as always policy has to deal with the balance between collective, societal interests and individual interests. Where in a conventional electric power system energy efficiency in almost all cases was both in the (economic) interest of the individual and of society, this might not be the case in some implementations of a decarbonized power system. If energy efficiency becomes a public good, it can be easily left out of economic and especially financial calculations.

The relation between energy efficiency and renewable energy is influenced by the technical, market and regulatory design of the electric power system. We will describe a centralized and a decentralized model where each has a specific emphasis on the importance of certain system levels and flexibility tools; see also Schleicher-Tappeser (2012) and Kuhn et al. (2016). Another model may be the grid-managing model, where the emphasis is on demand-side control.

In the **centralized model**, the flexibility challenge is dealt with at the highest level of the electric power system. This means that especially large storage and interconnection are used as flexibility tools and that generation at the local level is not particularly stimulated. This model also allows the integration of larger conventional power plants that are converted to run on renewable sources, e.g. biomass or hydrogen, as part of the storage system.

The consequence is that fixed costs, grid and storage costs, will increase and variable costs decrease. If this is reflected in retail tariffs, maybe to the extent that flat fees are offered, energy efficiency measures will be much less attractive from an individual economic point of view. However, from a societal perspective energy efficiency measures can be still attractive because they reduce demand and thereby the need for generation capacity and flexibility tools. Such a tariff structure will probably also increase inequality since households with a larger income tend to use more electricity which they then could obtain for almost the same costs as households with a low income that use less electricity.

In the **decentralized model**, the flexibility challenge is dealt with at the lowest level of the electric power system. This means that end-users are stimulated to generate the electricity they use themselves, including storage and demand-side control to minimize the impact of the variability of the VRE generation on the grid. Furthermore, as much as possible "regional flexibility" is used (Agora 2017). This is the "prosumer" model that emerges in several scenarios of the future electric power system (Parag and Sovacool 2016). In this model end-users directly profit from energy efficiency measures they take because these will decrease their investment in generation and flexibility. Not all end-users might be able to afford the required level of investment to generate and consume their own demand. However, a single end-user that does not invest will still profit from the investments from others.

10. This is an indirect interpretation of the Paris agreement that has as overall aim to keep the temperature increase well below 2 °C. This would already imply decarbonizing the electric power sector to a large extent. However, several countries opt for a complete decarbonization in order to use the remaining carbon budget for other purposes.

RECOMMENDATIONS FOR POLICY RESEARCH

The main aim of this paper is to provide a framework and ask the right questions of which the answers then can guide policy. The framework has been sketched in the foregoing chapter. This section provides some of the questions.

The first question is where on an aggregated, societal level the overall balance lies between energy efficiency measures and VRE generation capacity, including flexibility tools. Or said otherwise: how far can or need demand be reduced in order to generate this demand by means of VRE sources. A starting point is an estimate of the future demand at current efficiency levels, taking into account growth in demand by electrification. Then calculate LCOE for efficiency measures and generation capacity, including flexibility tools. The results can be presented in a graph showing a bandwidth for both generation and demand, where the overlapping zone represents a trade-off between increasing generation, including flexibility tools, and decreasing demand (see Figure 3 for a simple representation); this zone could also be seen as the zone of possible decarbonized solutions. Note that the LCOE offers only a (limited) economic perspective, whereas environmental and societal constraints, e.g. land-use, biodiversity, acceptance, also play a role.

The second question is which designs (technical, market and regulatory) can realize a decarbonized electric power system that lies within the bandwidth for generation and demand as indicated in the first question. In most studies a maximum of two elements out of the six of is taken into account: (VRE) generation and storage, generation and demand-control or generation and connection (see e.g. IEA RETD TCP reports). Table 1 indicates the main aspects for each of the elements in the three models. An important issue here is the role of markets; currently market design seems to be dominated by the view that VRE integration is a problem. Which markets are needed, how can they function including ensuring reliability on the long term, and what coordination is needed?

The third question is how energy efficiency improvements that are needed from an overall point of view can be realized. Or: how to deal with energy efficiency in a decarbonized electric power system? As shown before, this probably will depend on the design of the system, where in some designs the market may take care of energy efficiency where in other designs energy efficiency becomes a collective good.

A fourth question is how the transition from the current system can be managed. At many points this paper assumes that there is a decarbonized electric power system. However, although some countries do have a large share of renewables in their electric power system, e.g. Germany, Spain and Denmark, they are still far away from a fully decarbonized system. As the IEA (2014) has shown, starting conditions will heavily influence how more VRE can be (cost effectively) integrated in the electric power system. Likewise, starting conditions will influence the transition to a decarbonized electric power system.

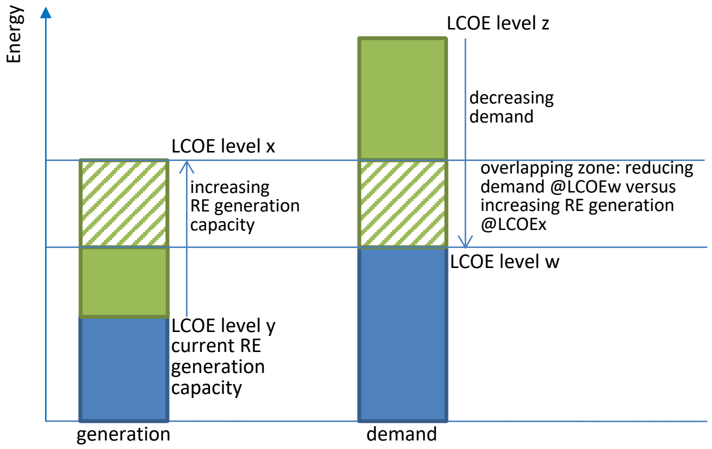

Figure 3. Comparing LCOE of generation and demand.

Table 1. Elements of the electric power system in three models.

	Model		
Elements	***centralized***	***decentralized***	***grid-managing***
generation	Large VRE plants, back-up by converted conventional power plants.	Focus on decentralized generation.	Mix of centralized and decentralized generation.
connection	Increased interconnection used as flexibility tool and to connect remote VRE plants.	Enhancing distribution grid to deal with increased decentralized generation.	Interconnection used as flexibility tool.
storage	Large storage facilities.	Storage at local level to increase self-consumption.	Storage to support the grid.
control	Demand-side control only for larger users.	Demand-side control to match local generation and demand.	Variations in generation as much as possible dealt with by demand-side control.
efficiency	Energy efficiency will become a public good.	Efficiency at end-users' decreases investment in generation and storage.	Focus on efficiencies that "support" demand-side control.

This paper did not explicitly discuss policies regarding energy efficiency or renewable energy, nor does it provide recommendations in this area; see e.g. Sovacool (2009) for some suggestions. The main reason is that the (recommendations on) policies will probably depend on the answers given to the questions above. Many policy suggestions in this area are "jumping to conclusions", mostly because they target an electric power system that is not fully decarbonized. Price incentives alone do not seem a solution, see Duane (2010), Ryan et al. (2011). More generally, it is thought that achieving a decarbonized electric power system is purely an economic problem and that the "right" markets will solve it; see e.g. Borenstein (2012) but note Rader and Norgaard (1996) for a more nuanced view. Achieving a decarbonized electric power system seems also to be a matter of (political) leadership, using windows of opportunity and creating public support.

References

Agora Energiewende. (2017). Smart-Market-Design in deutschen Verteilnetzen. Berlin: Agora Energiewende.

Andrade, J. R., & Bessa, R. J. (2017). Improving Renewable Energy Forecasting With a Grid of Numerical Weather Predictions. IEEE Transactions on Sustainable Energy, 8 (4), 1571–1580.

Borenstein, S. (2012). The Privat and Public Economics of Renewable Electricity Generation. The Journal of Economic Perspectives, 26 (1), 67–92.

Bruce-Konuah, A., & Gupta, R. (2017). Using smart energy storage to increase self-consumption of solar-generated electricity and reduce peak grid load at household and community level. eceee Summer Study proceedings, (pp. 1019–1029).

Cludius, J., Hermann, H., & Matthes, F. C. (2013). The Merit Order Effect of Wind and Photovoltaic Electricity Generation in Germany 2008–2012. Centre for Energy and Environmental Markets. Sydney: CEEM.

Dillig, M., Jung, M., & Karl, J. (2016). The impact of renewables on electricity prices in Germany – An estimation based on historic spot prices in the years 2011–2013. Renewable and Sustainable Energy Reviews, 57, 7–15.

Duane, T. P. (2010). Greening the Grid: Implementing Climate Change Policy Through Energy Efficiency, Renewable Portfolio Standards, and Strategic Transmission System Investments. Vermont Law Review, 34, 711–780.

EASAC. (2017). Valuing dedicated storage in electricity grids. EASAC.

European Commission. (2015). Energy Union Package. Brussels: European Commission.

Felder, F. A. (2011). Examining Electricity Price Suppression Due to Renewable Resources and Other Grid Investments. The Electricity Journal, 24 (4), 34–46.

Fuchs, G., Lunz, B., Leuthold, M., & Sauer, D. U. (2012). Technology Overview on Electricity Storage. Institut für Stromrichtertechnik und Elektrische Antriebe RWTH Aachen.

Gillich, A., Ford, A., Hewitt, M., Zagone, C., & Oakes, G. (2017). A smarter way to electrify heat – the balanced energy network approach to demand side response in the UK. eceee Summer Study proceedings, (pp. 1153–1163).

Green, R., & Vasilakos, N. (2011, March). The Long-term Impact of Wind Power on Electricity Prices and Generating Capacity. SSRN Electronic Journal.

Herring, H. (1999). Does energy efficiency save energy? The debate and its consequences. Applied Energy, 63, 209–226.

IEA. (2011). Harressing Variable Renewables. Paris: IEA.

IEA. (2014). Technology Roadmap; Energy Storage. Paris: IEA.

IEA. (2017). Energy Technology Perspectives 2017. Paris: IEA.

IEA. (2016). Re-powering Markets. Paris: IEA.

IRENA. (2014). REmap 2030: A Renewable Energy Roadmap. Abu Dhabi: IRENA.

Jargstorf, J., De Jonghe, C., & Belmans, R. (2015). Assessing the reflectivity of residential grid tariffs for a user reaction through photovoltaics and battery storage. Sustainable Energy, Grids and Networks, 1, 85–98.

Kok, J., Scheepers, M., & Kamphuis, I. (2010). Intelligence in Electricity Networks for Embedding Renewables and Distributed Generation. In R. R. Negenborn, & Z. H. Lukszo, Intelligent Infrastructures (pp. 179–209). Springer.

Kuhn, P., Huber, M., Dorfner, J., & Humacher, T. (2016). Challenges and opportunities of power systems from smart homes to super-grids. Ambio , 45 (Suppl. 1), 50–62.

Lampropoulos, I., Kling, W. L., Ribeiro, P. F., & Berg, J. v. (2013). History of Demand Side Management and Classification of Demand ResponseControl Schemes. Power and Energy Society General Meeting. Vancouver: IEEE.

Lechtenboehmer, S., Samadi, S., & Schneider, C. (2017). Energy efficiency quo vadis? – the role of energy efficiency in a 100% renewable future. eceee Summer Study proceedings, (pp. 171–181).

NordREG. (2011). NordREG report on the price peaks in the Nordic wholesale market during winter 2009–2010. Copenhagen.

Papalexopoulos, A., Hansen, C., Perrino, D., & Frowd, R. (2015). Modeling and Analysis of Wholesale Electricity Market Design: Understanding the Missing Money Problem. Golden: NREL.

Parag, Y., & Sovacool, B. (2016). Electricity market design for the prosumer area. Nature Energy, 1.

Paraschiv, F., Erni, D., & Pietsch, R. (2014). The impact of renewable energies on EEX day-ahead electricity prices. Energy Policy, 73, 196–210.

PwC. (2017). Blockchain – an opportunity for energy producers and consumers? PwC.

Rader, N. A., & Norgaard, R. B. (1996, July). Efficiency and Sustainability in Restructured Electricity Markets: The Renewables Portfolio Standard. The Electricity Journal, 37–49.

Ryan, L., Moarif, S., Levian, E., & Richard, B. (2011). Energy efficiency policy and carbon pricing. IEA. Paris: IEA.

Schleicher-Tappeser, R. (2012). How renewables will change electricity markets in the next five years. Energy Policy, 48, 64–75.

Sensfusz, Frank, Ragwitz, M., & Genoese, M. (2007). The Merit-order effect: A detailed analysis of the price effect of renewable electricity generation on sport market prices in Germany. Fraunhofer ISI. Karlsruhe: Fraunhofer ISI.

Sorrell, S., Dimitropoulos, J., & Sommerville, M. (2009). Empirical estimates of the direct rebound effect: A review. Energy Policy, 37, 1356–1371.

Sovacool, B. K. (2009). The importance of comprehensiveness in renewable electricity and energy-efficiency policy. Energy Policy, 37, 1529–1541.

Subkhankulova, D., Barrett, M., Manley, E., Baklanov, A., & McCullum, D. (2017). Balancing variable supply with flexible demand. eceee 2017 Summer Study (pp. 877–886). Stockholm: eceee.