The transition towards solar power; business as usual or a new role for incumbent grid operators?

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Abstract

In recent years, there has been a steady increase of 'solar prosumers', i.e. electricity consumers that have become producers of electricity using small scale solar Photovoltaic (PV) systems. In several countries, this development is underpinned by various policy enticement schemes with the goal of mitigating climate change in addition to the individual motivations of the prosumers including the attainment of self-sufficiency and independence from conventional electricity supply. For the continued expansion of solar PV systems, grid operators – also called distribution system operators (DSOs) – have been identified as key intermediary actors for the development and implementation of new services and business models that help balance variable surplus electricity from solar prosumers and facilitate a continued expansion of solar PV systems. However, the operations of DSOs are tightly regulated and the room of manoeuvre of DSOs is limited. At the same time, electricity grids are not equipped to handle the expansion of variable and distributed energy resources. Are DSOs currently transitioning into a new widened role in electric power systems which facilitates continued increase in solar prosumers? Or are they hindered by their path dependency and the stability of current socio-technical systems in which they are embedded?

Based on an empirical study of the Swedish energy system, this paper presents a description of the socio-technical electricity distribution system and current developments and system tensions from the point-of-view of DSOs in Sweden. The paper builds on a dataset of 175 local and regional DSOs together with semi-structured interviews with eight DSOs in Sweden.

The results show that path dependency of DSOs is a major factor and as such the transition of the role of local DSOs is likely to be a slow process. Despite ongoing discussions on the changing role of DSOs in Sweden, so far it has resulted in few concrete measures and DSOs typically apply a business-as-usual approach towards challenges with expansion of solar PVs, i.e. investing in increased transmission capacity. A changed role for DSOs could have the effect of more efficient expansion of distributed solar PV systems if it underpins DSOs' abilities to develop new system services. But such a change in role is hindered by current institutional settings as well as a lack in capacities and capabilities to develop new system services among a majority of the DSOs. To speed up the transition of local DSOs would require changes in current legislations together with efforts to stimulate innovation and learning processes of DSOs within current electricity systems.

Keywords: electricity system; distribution system operator, DSO; solar PV; distributed generation, DG; socio-technical transition

1. Introduction

Climate change mitigation is posing transformative pressure on the electricity sector in the transition to a low-carbon society, creating challenges for incumbent electricity industry which are struggling with path dependent lock-ins to current technological systems and business models. In recent years, transition studies have used various approaches, perspectives and methodologies to enrich our understanding of the opportunities and challenges associated with industrial, technological and societal changes in the context of low-carbon transitions (see e.g. Jacobsson and Bergek, 2011; Coenen, Benneworth and Truffer, 2012; Geels *et al.*, 2017). As already argued by Dahmén (1950) more than half a century ago, industrial and technological change is often characterised by tensions in the prevailing system where actors and institutions are subjected to the necessity of identifying and addressing opportunities that arise through innovation and transforming incumbent business models.

A large share of current global greenhouse gas emissions stem from electricity generation (IEA, 2015). In many countries government policies have promoted and supported different sources of Renewable Energy Technologies (RET) such as solar photovoltaics (PV) systems (IEA, 2013a), wind power (IEA, 2013b), and others. Within the European union, the renewable energy share has been rising steadily for the last decade (European Commission, 2017b). However, current electricity power systems are typically not equipped to handle the expansion of distributed generation (DG), such as solar and wind power. These renewable energy sources have variable and weather dependent power supply that poses new types of challenges for electricity systems compared to conventional generation technologies (Naber *et al.*, 2017). In order to manage a continued increase of DG there is a need for development and diffusion of products, services and methods that are complementary to solar and wind power technologies. A large share of these solutions requires local implementation, in proximity to the DG sites. For example, the most common problem in electricity grids with increased levels of solar PV relates to disturbances of voltage level. Solar PV systems can overload its point of connection to the grid, as well as overload network components causing both electricity lines and transformers to reach their thermal limits. These types of issues typically arise in areas with high level of solar PV penetrations and consequently needs to be managed locally (Mateo *et al.*, 2017).

The RET that for seven years in a row has received the largest share of new investments in renewable energies globally is solar power (Jaeger-Valdau, 2017) resulting in a rapid increase in solar PV systems during the last decade (IEA, 2017). Within the EU, the solar penetration rate has been influenced by political targets on both EU and a national level in order to mitigate climate change (European Commission, 2017). This development is also underpinned by the motivations of households who have installed small PV systems and view them as a mechanism of self-sufficiency and as a first step towards gaining independency from conventional electricity supply (Karakaya et al, 2015). Thus, there has been a steady increase of 'solar prosumers', i.e. electricity consumers that also have become producers of electricity (European Commission, 2017a; IEA, 2017; Jaeger-Valdau, 2017).

Grid operators – also called Distributed System Operators (DSOs) – have been identified as key actors for the continued expansion of RETs as they have the possibility to support the development and implementation of new services and business models that help balance the variable surplus electricity from solar prosumers and facilitate a continued expansion of solar PV systems (Simpson, 2017, Ruester *et al.*, 2014; Perez *et al.*, 2016; Mateo *et al.*, 2017; Zehir *et al.*, 2017).

The ongoing prosumer development and increasing levels of DG is changing the traditional value chain of electric power, from one-directional supply to a multi-directional value network of electric power. The RET diffusion will cause tensions on the existing infrastructure that distribute electricity where the DSOs are expected to transit from managing one-directional flows to bi- or even at points multi-directional flows of electric power in their respective grids. This challenges current configurations of low and medium volt electricity distribution grids which are designed for one-way distribution of centrally generated power (Mateo *et al.*, 2017; Zehir *et al.*, 2017). These two types of grids are seen illustrated in Figure 1, with a centralised and one-directional grid to the left and a decentralised and multi-directional grid to the right.

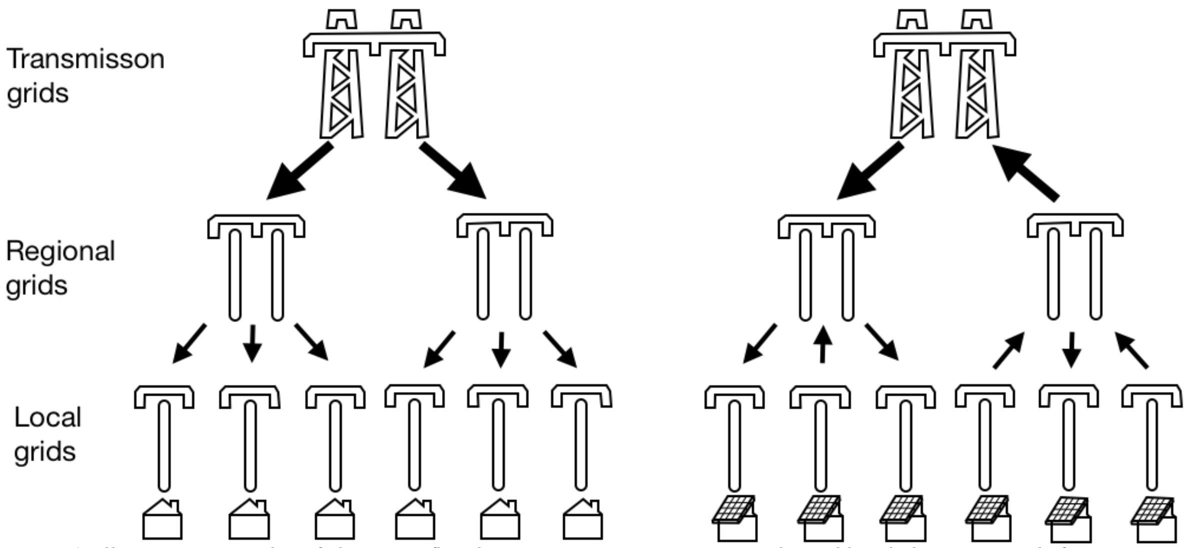

Figure 1. Illustrative examples of electricity flow between transmission-, regional-, and local electricity grids for conventional grids with centralized generation with one-directional flow (to the left) and grids with high level of distributed generation and multi-directional flows (to the right)

DSOs operate within a natural monopoly market, and their operations are tightly regulated. The tight regulation serves to secure that DSOs are limited in how much they can charge their customers and to protect the customer's integrity. But it also limits the room of manoeuvre of DSOs to manage technological disruption which changes the characteristics of existing electricity networks.

DSOs are part of complex network of actors in which they play an intermediary role. The role of inter-organizational networks in the energy area have not been sufficiently analysed (Kang and Hwang, 2016) and there are still uncertainties concerning which factors constitute barriers and which factors that promote growth of RET in current electricity systems (Ruggiero, Varho and Rikkonen, 2015).

Against this background, this paper aims at discussing the existing conditions for DSOs and analyse their potential role in the context of the current prosumer driven transition to a low carbon electricity system: Are grid operators currently transitioning into a new widened role in electric power systems which facilitates continued increase in solar prosumers, or are they hindered by their path dependency and the stability of current socio-technical systems in which they are embedded? To study this we identify and discuss which types of structural tensions that DSOs face in the context of the emergence and growth of solar prosumers in the socio-technical electricity system (actors, institutions and technologies). Based on this we then discuss what would happen if DSOs take a new role in the electricity system and what will happen if they don't.

We recognize that wind power poses similar challenges for DSOs as solar power, but in this paper, we delimit our focus to the tensions that arise from growth of solar power and increasing number of prosumers in electricity grids.

This paper consists of six sections. In the subsequent section, the literature on structural tensions and socio-technical transitions is discussed. Section 3 describes the research methodology of the paper while section 4 presents the findings. Section 5 discusses the results and, finally, section 6 concludes the study with implications and suggestions for further research.

2. Structural tensions in socio-technical transitions

There is a continuous process of coevolution and complex interplay between actors, institutions and technology in socio-technical systems undergoing transition (Johansson, 2017). Socio-technical transitions are "disruptive, contested, and non-linear processes" (Geels *et al.*, 2017, p.464). The dynamics of socio-technical transitions can be described as varying and changing misalignments or disequilibria between system elements. Historian Thomas Hughes (1983) used the terms 'salients' and 'reverse salients' to explain this dynamics of misalignment between system elements of an evolving socio-technical system. According to Hughes, reverse salients were defined and addressed as critical problems to be resolved in order to keep the momentum of the evolving system. Long before Thomas Hughes work on socio-technical systems the economist Erik Dahmén (1950) made a comparable description as he described how 'structural tensions' arise as complementarities in a 'development block' develop at different rates. Structural tensions stimulate investments in complementary elements or hold back the development of the prevailing systems (Laestadius, 2016; Blomkvist, Laestadius and Johansson, 2016; Carlsson 2016). A development block can be understood as a socio-technical system and the two concepts are interchangeable (Fridlund, 1999). In addition, drawing on knowledge from theories of socio-technical systems and transitions of socio-technical systems (e.g. Bijker, Hughes and Pinch, 1987; Hughes, 1992; Bijker, 1995; Rip and Kemp, 1998; Geels, 2002), the concept of structural tension can be used to describe misalignment/disequilibria between different elements in a socio-technical system transition.

To analyse tensions in an ongoing transition, it is helpful to define the perspective taken on the transition in question (Blomkvist and Johansson, 2014). A misalignment between two elements of a system could be described as a critical problem for one actor while it could be described as an opportunity or 'salient' for another type of actor in the same socio-technical system (Blomkvist and Johansson, 2016). It is acknowledged that the role of actor and agency in socio-technical transitions must be better integrated into transition studies (Fuenfschilling and Truffer, 2016; de Haan and Rotmans, 2018). An approach that was introduced by Johansson (2017) base the perspective of actors on socio-technical transitions on their role in value networks. The value network concept is derived from the field of strategic management research and is described in the works by e.g. Christensen (1997) and Allee (2000). It is a theoretically closely related concept to the concept of business models (e.g. Osterwalder et al. 2005 and Peppard & Rylander 2006). In this paper we define a value network as a network of actors that by change of tangible and intangible assets form an inter-organizational value creating process – similar to what Allee (2009) calls external-facing value networks. It can be argued that – by taking a strategic management perspective – value networks hold explanatory power of actors' intent and actions in socio-technical system transitions. There is reciprocity among actors in value networks that are interconnected in mutually beneficial relationsships, which strengthens their shared values and heuristics. Existing bonds in value networks influence the actions of organizations and may create path-dependence that hinder the development of new value creation processes. The core idea of using the value network concept in transition studies is similar to the idea behind the introduction of the concept 'streams' by de Haan and Rotmans (2018): "Streams are value sets enabled by the state of knowledge (science, technology or otherwise) and the available organising principles (e.g. economical, infrastructural) with which that knowledge could be harnessed to meet societal needs. When actors connect to streams the stream can be thought to direct their strategic actions." (de Haan and Rotmans, 2018, pp.276-277).

To categorize structural tensions in a socio-technical transition from the point-of-view of actors we take inspiration from the perspectives on socio-technical systems from the Multi-Level Perspective (MLP) approach (Geels 2002, 2004) and the Technological Innovation Systems (TIS) approach (Hekkert *et al.*, 2007; Bergek *et al.*, 2008; Markard, Hekkert and Jacobsson, 2015). In MLP studies the focal socio-technical system is called a socio-technical regime, a concept prominently derived from the works by Nelson and Winter (1982) and Bijker (1995). A socio-technical regime constitutes of three interlinked dimensions: (a) network of actors and social groups, (b) formal, normative and cognitive rules, and (c) material & technical elements (Verbong and Geels 2007). In TIS studies the structures of innovation systems can be categorized into (a) actors, (b) institutions and (c) technological structures (Markard, Hekkert and Jacobsson, 2015), which is a similar categorization compared to the dimensions of a socio-technical regime as described by Verbong and Geels (2007).

Inspired by these representations of socio-technical systems, we categorize structural tensions from the point-of-view of actors undergoing a socio-technical transition into three dimensions: between organization and technological structures, between organization and institutional structures, and between organization and organizational structures:

- The first dimension, between organization and technological structures, represents the tensions between an organization's current capacities and value network on the one hand and the technological and infrastructural developments in the socio-technical transition on the other.
- The second dimension, between organization and institutional structures, represents the tensions between an organization's current capacities and value network and the changes in regulation and legislation in the socio-technical transition.
- The third dimension, between organization and organizational structures, represents the tensions between an organization's capacity to reconfigure current value networks and develop new business models and the (real or potential) development of new value networks in the socio-technical system transition.

3. Methodology

This study explores, via a literature review and a case study, structural tensions in current electricity systems transition from a DSO perspective. As per described above, we categorize the empirical data into structural tensions in three different dimensions from an actor (DSO) perspective: DSO-technology; DSO-institutions; and DSO-organizations. The structural tensions concept is used to identify disequilibria between these different elements of existing socio-technical system structures that have emerged as different parts of the system have developed at different rates.

To validate the finding of a structural tension the method has been to triangulate findings (cf. Yin 2013) from different types of sources (academic literature, reports, statistics, interviews).

The literature review was done through keyword search on Science Direct by searching for 'DSO' OR 'DNO' in the journals Energy Policy (148 results), Research Policy (8 results), Energy Research & Social Science (16 results) and Environmental Innovation and Societal Transitions (2 results). This search was complemented by searching for 'DNO' OR 'DSO' AND 'technological transition' OR 'socio-technical system' in all journals on Science Direct (113 results). We then manually processed the search result to select the articles which included a DSO perspective on the ongoing energy system transition.

There are many different names for DSOs, including grid operators, grid companies, network operators, distribution network operators (DNO), etc. We chose to search for the words DSO and DNO because they are commonly used terms for grid operators, with DSO implying a more active role in operating the system (Bell and Gill, 2018).

We chose to delimit our case study to one single case: that of Sweden. There are – in spite of increasing interconnectedness and integration of electricity grids and markets within the EU – many nation-specific institutional factors which support the choice of spatially delimiting a case study to a specific nation. Sweden is a country with accessible statistics of DSOs and a history of going through the same unbundling-process of the energy markets as many other European nations.

In this single case study, we have gathered empirical data from mainly three types of primary sources: reports, statistic databases and interviews. The process of gathering empirical data can be described as exploratory and flexible (Eisenhardt 1989, p. 533).

The reports were mainly gathered from the authorities at a national level (The Swedish government, The Swedish Energy Markets Inspectorate, The Swedish Transmission System Operator Svenska Kraftnät, and the Swedish Energy Agency) and at a European level (the EU Commission) together with reports from industry associations and network forums and platforms at a Swedish and Nordic level (such as Energiföretagen, SwedishSmartGrid.se, Nordic Energy Research, etc.) and at an European level (such as EDSO, Eurelectric, CEDEC, etc.).

Available statistics were used to compile a dataset over all of Sweden's 175 local and regional DSOs. First a dataset was compiled using Svenska Kraftnät's database on registered DSOs in Sweden in 2016 (available at svk.se). Then additional organizational and financial information (such as information on turn-over, profits, year of registration, structure of ownership, affiliations, etc.) for each DSO by using online financial database services (allabolag.se) were manually added.

We have also interviewed respondents from the following eight Swedish DSOs:

- VänerEnergi
- SkövdeNät
- Skara Energi
- Tidaholms Energi
- Götene Elförening
- Lidköpings Elnät

- Pite Energi
- Sörbylunds Elnät.

We conducted the interviews through either individual interviews or interviews with a group of respondents from one or more DSOs. The interviews were semi-structured and discussions between the respondents were encouraged. All interviews have been audio recorded. The interviews ranged between 1-2 hours. The respondents in the interviews included CEOs and expert employees, with in total 17 individual respondents taking part in the interviews.

4. Structural tensions from a DSO perspective

In this section we first describe our case study and then presents our analysis of structural tensions.

4.1. The case study: The Swedish Electricity System and Swedish DSOs

The World Economic Forum has developed an Energy Transition Index (ETI) in which Sweden had one of the highest scores as one of the leading countries both in terms of energy system performance and energy system transition readiness (World Economic Forum, 2018). This high-end ranking is much due to Sweden's energy system and energy mix, with a high share of existing renewable and controllable energy sources in hydro power as well as a well-developed and high capacity transmission system.

In Sweden a DSO is responsible for measuring both generation and consumption in their respective grids and connecting new customers to the grid (Swedish electricity law 1997:857). The DSO is also responsible for operating and maintaining their respective grid and providing sufficient power quality. In other words, the DSO must monitor and make sure the voltage level is right in their grid and repair damaged equipment (e.g. when a tree falls over a distribution line).

Similar to DSOs in Europe (CEDEC *et al.*, 2018), there is a wide diversity of DSOs within Sweden. The organizational form of DSOs varies from economic associations to joint stock companies, industrial corporations, municipally owned, and to state owned DSOs. In 2016 there were 175 DSOs in Sweden. This figure can be compared to the number of DSOs in Germany, which has the highest amounts of DSOs in Europe with 896 DSOs (in 2010). A few other European countries only have one DSO (Mateo *et al.*, 2017). The number of DSOs in Sweden has varied over the years, as some has exited and other entered. Virtually all DSOs that have been registered in Sweden during the last two decades are wind farm associated companies, i.e. a DSO that has been formed in order to operate the electricity distribution and connection of a wind farm to the main grid. These companies do not run the same type of activities compared to a typical municipal DSO, as they typically only have a few connection points in their grids.

The traditional role of DSOs in Sweden has been to distribute centrally generated electricity. Hydropower and nuclear power still constitutes roughly 80% of the net electricity production in Sweden (out of the total annual electricity production of ~150 TWh). Wind power constitutes a little more than 10% and combined heat and power (CHP) plants in industry and district heating constitutes a little less than 10% of the annual electricity production, as seen in Figure 2. The share of nuclear power is however expected to fall with the planned dismantling of Sweden's four oldest nuclear reactors in the next coming years (SOU, 2017; Svenska Kraftnät, 2015).

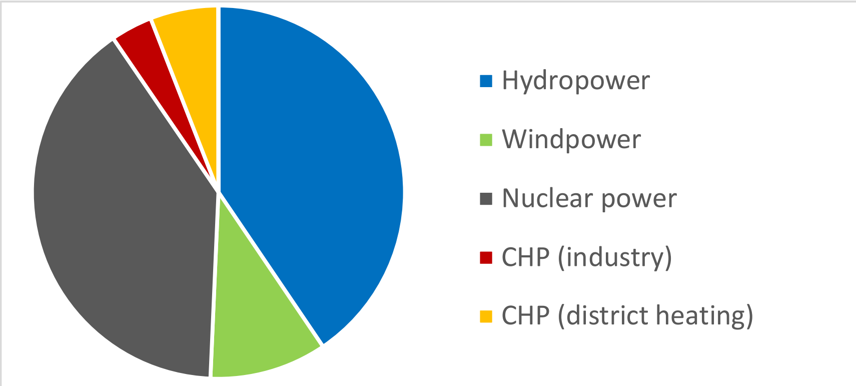

Figure 2. Share of net electricity production in Sweden during 2016 (The Swedish Energy Agency, 2018a)

It can be noted in Figure 2 that solar power is not represented in the statistics of net electricity production in Sweden in 2016. However, from relatively low initial levels, there is an ongoing and rapid expansion of implementation of solar PV in Sweden. The statistics for installation of solar PV systems in Sweden is given in Table 1. The statistics in Table 1 show that there was an increase in number of installed solar PV systems in the Swedish power system by more than 50 percent and a net increase in installed capacity by 65 percent from 2016 to 2017 (SCB, 2018). In spite of this rapid expansion, the total installed electricity generation capacity of solar PV in Sweden in 2017 only constituted about 0,5% of the total installed capacity in Sweden. The largest share of prosumers among different consumer groups in Sweden is found in the farming and agriculture category (Ei, 2017c).

	Number of Solar PV systems		**Installed capacity [MW]**	
	2016	**2017**	**2016**	**2017**
< 0,02 MW	8'543	12'863	64,99	103,84
0,02 – 1,00 MW	1'460	2,407	70,72	119,38
> 1,00 MW	3	6	4,32	7,76
Total	10'006	15'276	140,03	230,99

Table 1. Number of solar PV systems and installed capacity in Sweden divided by capacity class and year (SCB, 2018)

4.2. Structural tensions in the Swedish electricity system from a DSO perspective

We have listed an overview of the identified structural tensions from a DSO point-of-view in Table 2. These structural tensions are more elaborately described in the following sections.

DSO-technology tensions
Increasing levels of solar PV systems potentially requiring grid investments
Increasing levels of electronic appliances in the grid (causing voltage quality issues)
Increasing number of EVs potentially requiring grid investments
Monitoring and managing bi-directional and variable flows
DSO-institutional tensions
Complex and uncertain legislations with centralised decision making far from the influence of the average DSO
Uncertainties on how to distribute grid fees fairly among prosumers and other customers for costs caused by prosumers with systems that are less than 63 Ampere
Contradictory regulatory developments
The threat of diminishing contact with customers of the supplier centric model
Legal barriers to accessing and using energy storage facilities and demand side management services
Uncertainties on how to design grid fees and how to distribute grid fees fairly among prosumers and other customers
Uncertainties between division of responsibilities between system levels (prosumer, micro-grid, local distribution grid, regional distribution grid, transmission grid)

DSO-organizational tensions
Low level of current collaboration with TSO (mostly one-way top-down communication)
Lack of knowledge concerning alternatives to traditional grid investments and concerning how to navigate the complex market and manage legal uncertainties when developing new business models
Absence of energy system companies and 'aggregators' that supply with alternative solutions to traditional grid investments
Large variation in existing capacity among DSOs and risk of insufficient organizational and financial capacity (among a majority of the DSOs) if there is a (too) rapid expansion of solar power and electric vehicles
Risk of not being able to attract required competences to acquire capacity and build new capabilities

Table 2. An overview of structural tensions from a DSO point-of-view in ongoing socio-technical system transition

4.2.1. Technological tensions

With increasing levels of DG (wind and solar power) a number of technological problems for DSOs arise. Overvoltage is the most common problem limiting the PV connection in distribution grids, causing components to reach their thermal limit and consequently running the risk of malfunctioning (Mateo *et al.*, 2017). This is in line with our respondents that described how a typical single, dispersed house that installs a solar PV system is typically not a problem if it is below the 63 Ampere fee limit. But for houses far out in peripheral rural areas of the grid – e.g. a farm to which there are long distribution lines stretching – and in villages where there are several solar installations, *"problems from solar PV installations may arise even if the individual systems are each below the 63 Ampere limit"* (Interview, *DSO2*, 2017-12-06).

It is not only solar PV systems that cause increasing voltage-load challenges for DSOs, but also new electronic products and electric vehicles. According to out respondents, it has become increasingly difficult to maintain power quality in the grid with an increasing level of electronic gadgets. They have already taken measure to handle this problem, but at the same time the amounts of electronic products keep increasing. Our respondents did not perceive solar PV as a bigger problem compared to that of electric vehicles within the next coming couple of years. It is in rural areas, having longer distribution lines and generally weaker grids, where most problems are expected to arise from electric vehicle charging.

Large centralised generation is typically connected to the transmission grid, whereas solar PV systems and wind power plants are often connected to the medium- to low-voltage distribution grids, thus affecting the flow of electricity in the grids. Bi- or multi-directional electricity flows is one of the new challenges facing DSOs (Zehir *et al.*, 2017). There are still electricity meters in the Swedish grid which does not measure bi-directional flow, but only the amount of electricity passing through the meter (disregarding of which direction it flows). Therefore, DSOs need to make sure that a customer that have announced planned installation of a solar PV system have a smart meter that can measure the output of the customer's solar electricity to the grid. New meters also help DSOs monitor the grids in a more efficient manner. One respondent stated that there is a lot of new technology to help DSO manage their grids and to make the operations increasingly automated. And that this technology, for example new meters, is becoming cheaper and cheaper. The Swedish Energy Markets Inspectorate recommend all new smart meters to be installed with a capacity to measure the electricity consumption for every fifteen minutes (Ei, 2017a). But in one group of interviewed DSOs it was discussed if the measuring did not need to be even finer in order to meet potential future customer demands, perhaps even down to second-based metering. Another DSO stated that in fact their new meters were already ready to make measurements every minute, but the system they were running could only handle measurements down to every fifteen minutes.

4.2.2. Institutional tensions

Currently there are different ongoing and planned changes in the legislation on both EU and national levels affecting Swedish DSOs. There is an ongoing harmonization and integration of electricity markets in Europe, driven on by the EU (European Commission, 2016). At Swedish level the parliamentary energy agreement is expected to have a major impact on DSOs. However, decisions on how to interpret this cross-parliamentary energy agreement are still due to be made as the Swedish government is waiting for decisions at EU level to be made first (Prop. 2017/18:228).

The Swedish government support towards solar PV can currently be described as complex, involving direct subsidies, tax reductions and different kinds of reimbursements: Consumers may get direct subsidies for up to 30% of total costs of installing solar PV, alternatively get a tax deduction for the labour costs (so called "ROT-reduction") of installing solar PV up to 30% or 50'000 SEK (The Swedish Energy Agency, 2018b; Skatteverket, 2018b). Prosumers may sell their surplus electricity to the market through an electricity supplier and may also get reimbursements through the Swedish electricity certificate system (see law 2011:1200), which – for smaller producers – is typically also made through an electricity supplier. A tax reduction is also given for surplus solar electricity supplied to the grid at 0,6 SEK per kWh up to 30'000 kWh per year (Skatteverket, 2018c). Solar PV systems that supply less than 30´000 kWh per year are exempt from VAT (Skatteverket, 2018b) and solar PV system less than 255 kW in peak capacity are also exempt from energy taxation (Skatteverket, 2018a).

DSOs are not allowed to charge a prosumer for induced costs from the installation of solar PV systems if the total system is equal to or less than 63 Ampere (see Swedish electricity law 1997:857). The prosumer must however notify the DSO before installing a solar PV system, as the DSO may have to change the prosumer's meter to a smart meter. The DSO may also be required to grant a "grid value" (i.e. value for reducing grid losses) reimbursement to the prosumer (see Swedish regulation SFS 2017:1037). Currently Swedish DSOs have the possibility to charge their customers both a fixed fee for the size of the fuse and a variable fee depending on consumed energy, as well as the connection fee. In a recent proposition on the direction of energy policy in Sweden (Prop. 2017/18:228) a suggestion was made that Swedish DSOs are allowed to experiment with grid fees for a limited number of customers during a limited time frame. When asked about the possibility to experiment with new grid fees, several of our respondents hesitated to answer, possibly because this was the first time they had heard about this, while a few DSOs responded that it could be potentially interesting. In other discussions the interviewed DSOs had discussed the difficulties of adapting grid fees that are both cost based while at the same time *not* stifling continued installations of solar PV systems. In the current market set-up, DSOs may not charge anything extra for producers with generation smaller than 63 Ampere, even though DSOs may very well receive increased costs to solar PV systems that are well below the 63 Ampere limit, for example due to forced reinvestments in grid line capacity. If DSOs would adapt their grid fees to represent the actual grid cost for installed solar PV systems there would however be a risk that the prosumers fixed cost would be very high in relation to the variable costs (Swedish Energy Agency, 2016).

The proposition 2017/18:228 also covers the current plans of establishing a central data hub in Sweden that will encompass all metering of electricity market data in Sweden. One of the main reasons for establishing a data hub is to enable a so called ‘supplier centric model’. In this model all communication between electricity end-users is made with one contact, in this model being the electricity supplier (see the report Ei R2013:09). None of our respondents considered this to be a good idea. All of them wished to continue having direct communication with their grid customers.

The Swedish TSO, Svenska Kraftnät (SvK), have suggested that Swedish DSOs acquire a widened role with increased system responsibility, including grid balancing (SOU 2017:2). The response of one interviewed DSO was that it would be drastic if that would mean that they would be allowed to steer surplus electricity from their grid into overlaying grids. DSOs are required by law to connect new electricity generation facilities and are not *“at fault for the installation of new generation in our grid”* (Interview, DSO2, 2017-12-06). For DSOs to balance the frequency of the grid would however require access to either production, energy storage, or demand side management services. But DSOs in Sweden currently don’t have access to demand side management services, and they are also not allowed to own electricity production or energy storage asset other than to stabilise the grid (Swedish electricity law 1997:857). Since the unbundling of the Swedish energy market in the 1990s, DSOs are legally separated from electricity producers and retailers and have been limited in which operations they are allowed to undertake. For example, a DSO is only allowed to own batteries to stabilise their grids and reduce grid losses. A DSO can thus not use energy storage technologies for arbitrage, i.e. to store low-cost electricity on the grid and sell back to the grid at a later stage when the price is higher. This regulation also limits a DSO from sharing an energy storage asset with an affiliate energy producer, even though there might be strong synergies between the two organisations to do so. This effectively stops Sweden’s over 100 municipally owned DSOs to access and use their affiliates district heating facilities for energy storage. Assets which could otherwise act as potentially important energy storages for balancing surplus electricity from renewable and variable energy sources (Ramm *et al.*, 2017). Even if a DSO would purchase the balancing service from an energy service provider offering battery storage, it would be highly uneconomic as there is a double taxation on stored electricity during current legislations: the electricity is both taxed as the battery stores (or “consumes”) electricity and supply the electricity back (or “generates”) to the grid. Therefore, current regulations premiers so called “behind the meter” solutions when it does not pass the meter (the point of taxation).

Because current regulations premiers behind-the-meter solutions, there are also obstacles for the introduction of micro-grids into the Swedish electricity system. The energy company Eon has built a micro-grid in the village of Simris in south of Sweden that is run in island operation at times, but there have been raised voices as to the operation of this micro-grid by Eon is legal or not (Nohrstedt, 2018). As Eon both owns the production and energy storage facilities and act as DSO at this micro-grid site, it is technically the DSO that supplies electricity to the customers when the micro-grid is run in island operation. Also, when Eon runs the micro-grid in island operation, they technically take system responsibility for that part of the grid – which is otherwise (still) the responsibility of the Swedish TSO. This serves as an example of the challenges concerning the legal room-of-manoeuvre for DSOs relating to micro-grids and for the difficulties of how to define responsibilities between actors at different levels (household, micro-grid, local grid, regional grid, transmission grid) in the electricity system.

4.2.3. Organizational tensions

The Swedish TSO Svenska Kraftnät consider that the level of collaboration and coordination within distribution grids need to increase, both between TSO and DSO and between consumer/prosumer and DSO (SOU 2017:2). However, our respondents see a threat of managing increased level of collaboration with consumers and prosumers if the planned establishment of a supply-centric model is introduced. Also – considering increased level of collaboration between TSO and DSO – a couple of respondents expressed their concern of a top-down steering attitude in Sweden, where the views of DSOs were not considered or integrated in the development of new legislation. The respondents implied that there is currently not much collaboration between TSO and DSO, rather a one-way communication from the TSO to DSO. On the same note, one of our respondents stated that DSOs are good at adapting: "*You never say no, but make sure to change in order to keep everything 'in-house'*" (Interview, *DSO1*, 2017-10-02), meaning that DSOs do not argue against the authorities, but find ways to keep business-as-usual going to the extent it is possible. Even if DSOs and affiliated electricity suppliers are demanded to be legally separated, in practice they are often working in close proximity to each other.

According to our respondents, the complexity of current markets and legislations act as barriers for them to find alternatives to traditional grid investments and develop new business models. One of our respondents referred to a Swedish power electronics professor that had stated that there is not any existing system that is as difficult to analyse as a masked electricity grid, so for them as a DSO to manage developing new business models in this complex system is regarded to be too difficult: *"To cope with thinking about business models and opportunities, that, I am not sure if we, small as we are, are able to do. In that case we have to let the industry as whole show the way and point a direction. Just the question of regulation concerning energy storage, is a tough nut to crack"* (Interview, DSO2, 2017-12-06).

An illustration of the current value networks surrounding DSOs in Sweden based on existing business and market models are given in Figure 3. In Figure 3 the actors in the electricity system is represented by boxes and exchanges between these actors are characterized by the arrows. The exchanges of mostly tangible assets are represented by solid arrow lines and the exchanges of mostly intangible assets by doted lines. The electricity flow from generation to consumption is represented by the solid yellow lines. While not claiming that Figure 3 is fully comprehensive and exhaustive, it serves to illustrate the current role and complexity of the value network in which DSOs operate.

One DSO described the difficulty and complexity of finding the right measures for allocating and distributing grid costs induced by generation in their grids, and used the example of when a wind park of 35 MW in their grid produces more than is being consumed in their grid so they are forced to feed power to the main grid: *"...when we feed power to Vattenfall's [overlying regional] grid – it happens every year – especially at one point, it is quite expensive [...], and we try to transfer that cost on to the wind power company. We have a right to take a fee from larger producers but not smaller. And it is really Vattenfall's production company that is the large actor that could pump the hydro storage magazines. It is a very complicated market and complicated system".* (Interview, *DSO2*, 20171206).

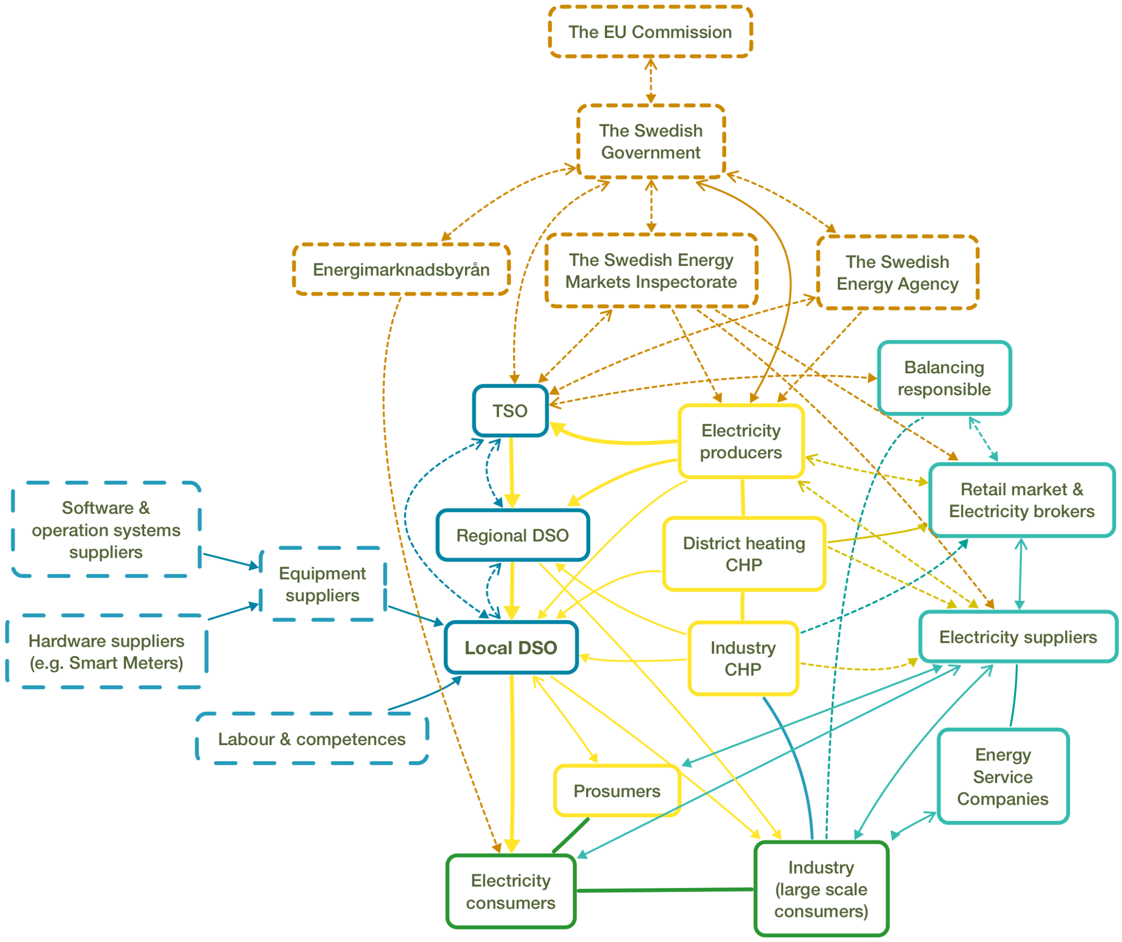

Figure 3. Illustration of the value network of DSOs in Sweden, based on (Ei, 2015) and (Zhong, 2018)

According to the Swedish Energy Markets Inspectorate, Swedish DSOs have shown little interest in acquiring demand flexibility from energy service companies in Sweden (Ei, 2017b). But according to our respondents, it is not because of lacking interest but because of lacking market offerings and knowledge concerning alternatives to the traditional methods. Energy service companies that aggregates/combine the control of demand and/or generation of several consumers and prosumers to offer demand response or generation curtailment services to the DSO are called 'aggregators'. In a report for the European Commission it is suggested that the role of aggregators will increase in significance for the integration of distributed generation in existing electricity systems (Damsgaard *et al.*, 2015). However, none of our respondents have had any contact with any such type of company.

The financial capacity of Swedish DSOs varies, ranging from the smallest DSO with seven connected households and a turnover of less than EUR 5'000 per year, to the largest DSOs which have up to 950'000 connected households and over 100 MSEK in annual turnover. The share of Swedish electricity grid customers is distributed in a manner where the three largest DSOs (Ellevio AB, Eon Elnät Sverige AB, and Vattenfall Eldistribution AB) have half the share of all the customers (Ei, 2017c). Out of the 172 remaining DSOs, three in five are municipally owned and belong to the middle-sized (based on turn-over) group of DSOs. These middle sized owned DSOs does not have the same type of organizational or financial capacity as the largest DSOs, and among these middle-sized DSOs there is an awareness that if the levels of solar PV systems would increase dramatically in a relatively short timeframe it would pose large capacity problems for them. As one of our respondents expressed: *"It could become a ketchup effect of this… if the prices become low enough and the technology is* *relatively simple, then it could explode [...] and we will be caught with our pants down"* (Interview, *DSO2*, 2017-12-06). Related to this issue, our respondents considered that there are difficulties with recruiting and acquiring needed competence. It is already difficult for them as a DSO to acquire competence and resources to manage their current tasks, and they are concerned that it will be even more difficult to attract competence for managing future requirements and managing new business models and legal aspects. This is especially difficult for smaller sized DSOs.

5. Discussion

In this paper we have seen that the development of DG and electric vehicles already pose as challenges for DSOs and that DSOs typically apply a business-as-usual approach to these challenges, i.e. if grid investments are required the DSOs invest in increased transmission capacity. This business-as-usual approach should not be described as a result of transformation pressure, but rather a result of path dependency and lack of viable alternatives. We have identified several significant structural tensions that DSOs face in current transition of the energy system. These tensions put significant pressure on DSOs to change their role and contribute to a reconfiguration of the current value network. We have also described the variation of financial capacity in the DSO population. In Sweden the largest DSOs have a turnover over EUR 100 million while the smallest DSO has less than EUR 10'000. This indicates that different DSOs have different capacities and capabilities to address and manage the structural tensions which we have described in this paper.

Current regulatory issues regarding grid fees, contacts with customers, barriers to access energy storages and complex legislations (that DSOs find difficult to interpret) as well as organizational issues regarding capacity and capability to reconfigure existing value networks – in sum – result in path dependent lock-ins of current value networks and significant barriers for DSOs to develop new services and adopt new business models. This indicates that the transition of the role of DSOs will likely be a slow process.

There are good reasons to believe that a changed role of DSOs would contribute to a more efficient expansion of distributed solar PV systems if it underpins DSOs' abilities to develop new system services. DSOs are situated in a central and intermediary position in current electricity systems (see Figure 3). Intermediary actors play an important role in building and reconfiguring systems and supporting innovation (Bush *et al.*, 2017) and therefore this paper suggests that the role of DSOs should be considered of significant importance for the ongoing transition to a low-carbon electricity system. While DSOs are currently hindered to act, regulatory changes could result in the active participation of DSOs in addressing many of the listed structural tensions in this paper. One measure that can be done to support an increase in DSO capacity and capabilities to manage the prosumer driven transition is to allow and support the participation of DSOs in experimental activities that promotes learning processes of DSOs and formation of new partnerships. This could also contribute to market formation and ancillary actors, e.g. energy service companies and solar PV suppliers, to develop new services and offerings to DSOs. Another example is that a changed role of DSOs could possibly contribute to more resource efficient expansion of solar power by contributing to closer interconnectedness between the electricity and heating systems. In the Swedish case, this means that Swedish DSOs could integrate a higher share of solar PV in their grids if they could access and utilise the energy storage potential in the hundreds of district heating systems and over one million heat pumps in Sweden. Another example is that a changed role for DSOs where DSOs are allowed to influence and steer the deployment and curtailment of DG through grid tariffs could potentially allow for a much higher deployment rate of solar power in our existing systems (Lingfors, 2017; Luthander, Lingfors and Widén, 2017). This would also address the current dilemma concerning how to adapt tariffs to represent actual costs of the installation of solar PV systems for DSOs while at the same time not stifling expansion of further solar PV system installations in their grids. Either the grid-costs for the installation of solar PV system are taken by the DSO, i.e. spread among the DSOs customers, or by the owner of the PV system. The latter alternative would likely decrease the rate of further PV installations, at least in grid areas poorly suited for intermittent electricity generation, but on the other hand promote installations of solar PV systems where it would best fit with the existing system.

While there is virtually no future electricity system scenario where the DSO is completely bypassed, there is the possibility that the role of DSOs will continue with business-as-usual and the tensions that are listed in this paper are addressed by other actors, such as energy service companies and aggregators. For example, the abovementioned access to district heating and residential heating as energy storage facilities could be made by energy service companies or aggregators instead, considering that there would be a market for such energy storage services. However, this paper indicates that if the role of the DSO as a central and intermediary actor in a resource efficient transition to a low-carbon electricity system would not be acknowledged by policy makers, there is an evident risk of significantly slowing down the transition process of the electricity system.

The value network perspective used in this paper can be argued to supply some explanation to the 'bounded rationality of actors' (Simon, 1955), but we acknowledge that DSOs may also have agendas that are not represented by their current value network roles. Another consideration concerning the approach we have used is that it has focused on structures which, almost by definition, are static entities. TIS studies have developed an approach which combines functions with structures in order for a dynamic approach to technological change (Hekkert *et al.*, 2007). While the TIS approach focuses on analysis of current processes and historical events, our approach – by focusing on the structural *tensions* – put focus on the area and stimulus of entrepreneurial and policy activity, i.e. what is required for the socio-technical system to develop new structures. And as such, it serves the aim of this study. A final consideration to highlight is the delimitation of using Sweden as a case, which limits the possibility to generalize from this article, especially to areas outside of the EU.

This paper shows that there are significant incentives to change the role of the DSOs, resulting in substantial potential benefits. That said, there are at the same time lock-ins and significant barriers to change indicating that such a transformation process will become quite slow, if not policy makers intervene facilitating the required changes.

6. Conclusions, implications and further research

In this paper we have explored the system tensions in the Swedish electricity system from the perspective of distributed system operators (DSOs). DSOs are key actors in reconfiguring existing value networks and play a potentially central role in the continued transition towards a low-carbon electricity system. Due to the structural tensions directly affecting the activities of DSOs we conclude that, in order to promote continued growth of RET, there are strong incentives to change the current role of DSO. But there are significant lock-in effects and barriers which hinders and slows down the change processed of DSOs. This in turn encourages policy intervention. Some of the most important tensions that need to be addressed concern grid tariffs (that distribute costs fairly without stifling the expansion of solar PV), legislation relating to energy storage assets, and lack of capacity and capabilities to reconfigure current value networks. This last point could be addressed by promoting experimental activities that promotes learning processes of DSOs and formation of new partnerships, which could contribute to increased level of innovation and reconfiguration of current value networks, thus supporting the transition to a low-carbon electricity system.

6.1. Suggested future research

This paper shows that there is significant pressure on DSOs to change, but this paper does not indicate *how* the role of DSOs could or should be changed. There are different alternative ways forward for DSOs and we suggest further research on how different market and business models would address and stimulate solutions to the identified structural tensions described in this article. This could for example be done through value network scenario analysis where the changed role of DSOs varies with different scenarios, to study the capacity and capabilities of different value networks as a whole, and for different market models.

We also suggest making a comparison of the role of DSOs in different transitions of electricity systems in different countries. This could give guidance on national level as well as input to the potential harmonisation on a EU level.

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