Transitioning from the traditional to the smart grid: Lessons learned from closed-loop supply chains

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Abstract—**In the past two decades supply chain management has moved towards greater decentralization and multidirectional flows characterized by greater volatility. The experience gained in this transformation has culminated in the concept of closed-loop supply chains. Meanwhile, the electric power landscape is facing a similar development, resulting in new challenges for its centerpiece, the grid. This paper draws on the knowledge acquired by closed-loop supply chain theory and applies it to the electric power landscape via a case study research focusing on Germany. By way of doing so, this article expands the concept of closed-loop supply chains and pinpoints the development the electric power landscape is about to face. This will, in particular, help mapping what the future smart grid will have to withstand. Clear policy implications can be derived from the findings. It is shown that the current one-sided promotion of renewable energy sources needs to be complemented by grid fortifications.**

Keywords: smart grid, supply chain management, closed-loop supply chains, reverse logistics, distributed generation, prosumers

I. INTRODUCTION

The smart grid is to pave the way for the future electric power landscape. Pitfalls of the existing grid infrastructure such as the dependence on conventional input sources are to be overcome by better deployment of renewable energy sources and adding a layer of information and communication technology. The smart grid is to be self-healing and allow for remote steering, better control and monitoring [1]. But if it is to cater for and facilitate future developments prevalent in the entire electric power sector, these developments need to be pinpointed. One way of discerning the trends and uncovering the dynamics inherent to the unfolding development is to draw on the development another industry took when facing similar structural changes and challenges. Because supply chain management features a similar environment and went through a similar development, this industry provides such an example.

Supply chain management and electric power management exhibit common characteristics and feature great similarities of techniques that come to play when managing the respective environment. The classical value chain featuring sourcing, production, transportation and distribution on the supply chain management side has a similar shape in the electric power landscape. There, electric power is generated drawing on manifold energy sources, converted, subsequently transmitted and distributed [2]. Both disciplines face supply and demand uncertainty, for example stemming from volatile input source like wind or supply disruptions and fluctuating demand. Both industries also face an increasing bargaining power of customers and similar circumstances and trade-offs regarding their respective sourcing decisions. Key analogies and common characteristics are highlighted in Table 1.

What is more, both sectors share the development from centralized generation and unidirectional flows to decentralization and multidirectional flows. Triggered by legislation and economic incentives an increasing amount of customers have started returning products to the original equipment manufacturer around 20 years ago. These flows are volatile, hard to predict and steer and resulted in the growing importance of reverse logistics [3]. To better address the challenges inherent to the development of companies being legally and economically coerced to overhaul their production structures and processes the theory of closed-loop supply chains has been developed. Meanwhile, the electric power landscape is facing an analogous development. Borne by matured technologies such as photovoltaic systems which draw on renewable energy sources, many customers not only consume electric power but as prosumers increasingly feed electric power into the grid [4]. The generation units deployed are usually of small scale but dispersed, giving rise to greater decentralization and distributed generation [5]. Yet, the resulting flows into the grid are hard to forecast, influence and volatile, coercing transmission system operators (TSO) to come to terms with them. But while this trend has only recently started in the electric power landscape, supply chain management has about 20 years of experience in dealing with these multidirectional and volatile flows from dispersed sources. This experience, which cumulates in the concept of closed-loop supply chains, can help uncover what developments the electric power landscape and therewith the grid are going to face in the future.

It is the aim of this paper to pinpoint the looming changes and challenges for the grid by drawing on supply chain management knowledge and experience. By way of doing so, the concept of closed-loop supply chains will be extended and tailored to the electric power landscape such that future developments the grid will have to cater for will be sketched. This will help policy makers fine-tune regulations and re-align the focus of attention as well as the provision of funds. On a broader scale, this paper paves the way for cross-industry knowledge exchange between supply chain management and electric power management.

Table 1: Common characteristics and analogies

Supply Chain Management	**Electric Power Management**
Sourcing, production, transportation, distribution	Sourcing, generation, transmission, distribution
Safety stock	Peak generation capacity / balancing power
Stock-out	Outage
Network design	Electrical power network design
Logistics infrastructure (highways, trucks, shipping)	Electrical grid
3PLs	Transmission System Operators
Load (weight) distribution	Load balancing
Growing supply & demand uncertainty	
Increasing customer power	
Development towards decentralization	
Growing importance of reverse logistics, holistic network design needed → *closed-loop supply chains*	Increasing amount of bidirectional flows, impact on network structure → *no according conceptualization yet*

This paper is organized as follows: the following Section II provides a review of existing and entangled work, providing the basis for the development of the model, which is presented in Section III. The findings of the executed case study research are presented in Section IV. Section V discusses the implications for the development of the smart grid.

II. Related work

Traditional supply chain management was preoccupied with organizing the flows of goods or goods-related elements from various sources and points of supply to the final point of consumption [6]. This firm conception of unidirectional flows of goods (from the point of origin towards the final point of consumption) was challenged when legislation and economic incentives forced companies to accept and cater for return flows. Triggered by regulation and promotion schemes customers started to increasingly return electronic devices, cars and other consumer goods to where they had bought them if they opted for a new product or had other reasons to return the product. Initially mainly seen as a burden, many companies started seeing these return flows as a means of sourcing and fine-tuned the existing network structure with regard to these new streams. To make best use of the return flows, the concept of reverse logistics has been coined. Reverse logistics targets flows opposite to the traditional forward direction [7]. As such they also occur within the company, for example if by-products or left-overs from production are re-used at another point or form. The flows are organized and processed such that as much economic value as possible is recovered. To account for this objective new ways of product recovery management have been formulated, involving several steps and taking various forms such as repair, remanufacturing, recycling or even direct resale [8]. Finally, to address the challenges of these structural changes taking place, the theory of closed-loop supply chains has been developed [9]. The main ingredients of the concept of closed-loop supply chains are forward and reverse flows. The novelty of the concept is that both streams are considered at the same time and are organized with regard to one another in order to increase total benefits. For this to be fully realized, the customer, being recipient of the forward flows and the initiator of the reverse flows has a critical role.

In the past twenty years the magnitude of the reverse flows has increased significantly, meanwhile constituting a significant share of total logistic activities for many sectors. An important characteristic of the reverse flows is that they can be initiated at manifold places, are hard to predict and steer and often are highly seasonable and volatile [10]. Because of the external nature of these flows, optimizing the whole network structure and fine-tuning the operations becomes a more complex task. De Brito and Dekker (2003) have put forward a model to address the challenges arising from this development [3]. It is the scope of this paper to apply the entangled concept of closed-loop supply chains to the electric power landscape. This will help capturing the driving forces and dynamics transforming the electric power landscape. It involves steps like pinpointing the elements which need special attention in the electric power discipline and overhauling the typology, since a priori the emphasis has been laid on different aspects and a different terminology has been adopted by the closed-loop supply chain discipline.

III. Model development & Application

The model to be developed is to discern the driving forces fuelling the changes in the electric power landscape as well as the pivotal developments resulting from that. It is thus to help ask the right questions when analyzing the electric power landscape´s current state, future development and potential challenges. For the supply chain management domain a similar endeavor has been undertaken by De Brito and Dekker (2003, see [3]). They focus on the driving forces in order to uncover what spurs the transformations reshaping the supply chain management landscape. By asking who is involved, what is being returned, how the reverse logistics processes are executed in practice and why things are returned in the first place they explore how and why the transformations are taking place and sketch future developments. Due to the similar focus their model serves as a blueprint for the model presented in this paper. And in fact, the four focal interrogatives they use – who, what, how and why - can be applied in a very similar fashion to the electric power landscape. Yet, the necessity to instantaneously match supply and demand requires adding an additional dimension, a time and thus “when” dimension. The model will be developed and presented in the ensuing section. Afterwards, the cases for its application will be presented. In a final step the key topics representing the transformations taking place will be delineated.

A. *Model development*

When discerning the driving forces in the electric power landscape, a first question to ask is *who* is involved. Traditionally, utilities were the dominant players in the electric power landscape, but municipalities and TSOs are also important actors. More recently prosumers have gained importance, already representing several hundred thousand households in some countries. Governmental agencies also exert influence in terms of regulations and promotions and are among the decisive actors.

What is fed into the grid? There are significant differences in terms of output quantity and reliability for the different generation units. Conventional power plants tend to be huge (often having a peak capacity of several hundred MW) in order to capitalize on economies of scale and their centralized position [11]. Generation units drawing on renewable energy sources like wind turbines or solar installations have varying sizes. If they are deployed by individual households, however, they are often smaller (many of them having a peak capacity of several kW only), giving rise to the notion of distributed generation [12]. Yet, since they effectively rely on hard-to-steer external parameters like wind or sunshine the fluctuation of generation is much higher than for conventional input sources like coal or gas.

How is the transmission & distribution process organized? In traditional electric power landscapes characterized by huge and centralized power plants the transmission lines catering to bulk transmission assume a prominent role. In a decentralized power landscape, however, where small-scale generation units are installed close to the electrical load the transmission level is increasingly circumvented and the distribution grid takes a more important role [5].

Why are reverse flows initiated and accepted? This question targets two distinct groups, the sender and receiver of reverse flows [3]. Reverse flows are initiated by customers who previously had only been consuming but recently started generating as well and feed surplus electricity into the grid. In traditional electric power landscapes individual households have few reasons and possibilities to generate their own electric power. In a modern and decentralized electric power landscape, however, there are several reasons for households and individuals to become prosumers [4]. Incentivized by favorable regulation and guaranteed feed-in schemes households might look for a financially rewarding investment or act out of environmental concern. In light of rising electricity prices installing a captive generation unit can also be a means to hedge against rising electricity costs and to cater for greater autarky. In many countries, the TSOs are legally obliged to remunerate the electric power generated by prosumers according to a fixed feed-in tariff scheme.

When is the loop closed? This question pertains to the significance of the reverse flows and has two distinct levels, an operational and a strategic one. The operational level is to capture whether operational structures or procedures need to be changed in light of the reverse flows. While the processing or re-using of reverse flows can often be postponed on the supply chain management side, this is not possible on the electric power side. Here, instant matching of supply and demand is needed at all times. In the absence of large-scale storage capacities this means that the reverse flows require immediate reaction. The strategic level targets the strategic significance of the reverse flows and decentralization. It also captures the "time factor" at which new developments like the prosumer trend prevail and which status they currently have [13, p.11]. This is especially useful for systems under transformation, which are in the transition phase from one state to another. In traditional electric power landscapes reverse flows hardly occur and therefore there is little need to come to terms with them. However, in more modern and decentralized electric power landscapes in which many prosumers feed excess electric power into the grid it is a strategic imperative to deal with the reverse flows.

B. *Case studies*

The general arrangement of the five dimensions that form the model is mapped in Figure 1. Since it is essential to the aim of this paper to uncover and understand the dynamics present in the electric power landscape, a case study approach has been pursued [14]. The model was used to derive the right questions when analyzing the cases. Focusing on Germany, a municipal utility, an electric installation company, a TSO and a prosumer household have been selected as cases. They cover the main actors and elements present in the electric power landscape as well as the central topics under transformation. The cases have been scrutinized using semi-structured interviews and complementary information sources such as press releases, financial reports and company websites. The interviewees were senior managers dealing with topics such as distributed generation, the flows from prosumers into the grid, the roll-out of devices entangled to the smart grid environment and the management of the grid as such.

C. *Key topics in the changing electric power landscape*

In order to sketch what developments the electric power landscape as a whole is going to face it helps to delineate key areas representing the transformations taking place. Renewable energy sources deployed at a small scale and hence referred to as distributed generation have sparked the developments in the electric power sector, which ultimately resulted in the prosumer movement. Thus, the pivotal topics are renewable energy sources, distributed generation and prosumers. As such, these topics are targeted by the dimensions of the model and are

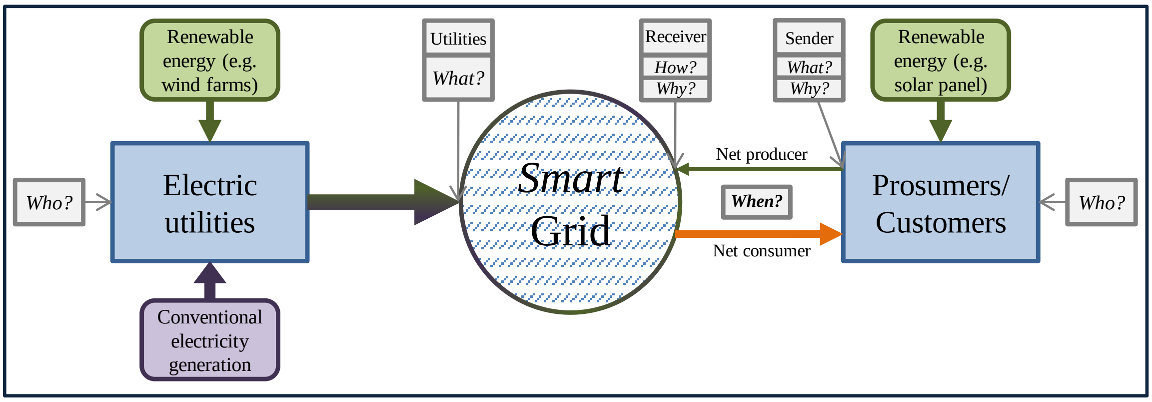

Figure 1: Adapted closed-loop supply chain model

embodied in it. The prosumers are listed as decisive actors. What they feed into the grid stems from renewable energy sources. Compared to what is generated by conventionally fuelled technologies the flows from prosumers have a smaller scale and come from more numerous but scattered locations. Therefore, how these flows are fed into the grid is different in that a different level of the grid is targeted, namely, the distribution grid. As a consequence of this and the nature of these flows, this phenomenon is described as distributed generation. Furthermore, why customers become prosumers in the first place is explored, and when the reverse flows occur and are of significance on a total level.

The insights gained from the cases with regard to the state, outlook and challenges of these central topics is discussed in the following. The developments in these areas in turn have profound implications for the requirements and development of the smart grid, another pivotal topic. Therefore the implications for the smart grid will be discussed after having laid out the direction in which the electric power landscape as a whole is developing.

IV. Findings

A. *Renewable energy sources*

On a total level, renewable energy sources are already an important pillar for the electric power generation in many countries. In Germany, they account for 20% of total input sources for the electric power generation and are second to only brown coal (24%) in this respect [15]. Thanks to the guaranteed feed-in tariffs, generation units drawing on renewable energy sources are attractive for a wide range of customers since the investment has an almost guaranteed yield. These favorable feed-in tariffs and the fact that they are guaranteed for twenty years were found to be the decisive reason for the recent rush on renewable energy sources by households or individuals. The promotion of renewable energy sources furthers the goal of implementing ambitious CO_2-reduction targets and reduces the dependency on finite fossil fuels. Promoting renewable energy sources has created new jobs but also requires increasing public funding since the favorable feed-in scheme needs to be financed. While the tariffs are decreasing gradually, so are the prices for the underlying technology like solar panels. Therefore, the trend towards renewable energy sources will not cease abruptly anytime soon.

While immediately reducing electricity costs or getting monthly remunerations, both households and companies can furthermore hedge against rising electricity costs. Except for acquisition costs and maintenance, installations like photovoltaic systems do not incur running expenses so that an investment will pay off even more with rising electricity prices charged by the brokers.

As reported by the TSO the rising shares of renewable energy sources in terms of total electric power generation requires operative adjustment and strategic action because the flows are extremely volatile and elude precise forecasting. Negligible flows at one day and generation close to the total load the other day are not unusual. Therefore, ample balancing power to cushion and even out the volatility is needed. Furthermore, since flows from input sources like wind or sun cannot be steered and (at least for wind power) do not always parallel consumption the development of storage capacities remains a central task. In that sense storage capacities pose a bottleneck since in their absence a situation might be hazarded in which electric power generation from renewable energy sources might be partially limited by disconnection because it otherwise would exceed consumption and threaten the grid stability. Then, the energy produced in the cleanest fashion would directly be wasted.

B. *Distributed generation*

Distributed generation implies a shift in terms of generation unit size, their input, location and also ownership [5]. Instead of large and centralized conventional power plants owned by few dominant utilities, more dispersed small-scale generation units powered by renewable energy sources and owned by individuals or small collectives come into play. This shift is already taking place. While the dominant utilities have missed out on jumping on the bandwagon of renewable energy sources and decentralization, many households, supported by the favorable feed-in tariffs have. In Germany, the majority of the installed generation capacity drawing on renewable energy sources is owned by households and farmers [13]. Almost half of these installations have a peak capacity of less than 100kW [16]. Aggregating these small-scale flows and conceiving them as virtual power plants can help better handle the decentralized generation landscape in a portfolio management fashion [17].

Rural areas are predestined for the deployment of small-scale renewable energy sources because space is abundant and relatively cheap. Furthermore, in rural areas more households tend to own the house they live in, which can be a requirement for installing photovoltaic systems and the like. As a result, some rural areas are already net surplus areas during sunny weekend days. With unabated addition of installations this trend will continue. It becomes especially important, then, to link these net surplus areas to net consumption areas. Otherwise installations might have to be switched off remotely in case of insufficient load. A trend that has prevailed among the cases is the attempt to better link the rural hinterland to cities. Naturally, because of expensive and scarce land as well as higher population density and therefore higher energy consumption, cities cannot easily switch to small-scale renewable energy sources. But they can be supplied by electric power directly or the necessary input sources from the rural hinterland. For example, the electric installation company has recently installed what it calls a ”countryside supplying the city” solution. It has built a seven kilometer long pipeline in which farmers in the rural area feed in biogas, which then fires cogeneration units in the city. With more offshore wind parks being completed soon and therewith the spatial separation between generation and consumption increasing it becomes increasingly pressing to better link net production and net consumption areas.

C. *Prosumers*

The appearance and rise of the prosumers embodies the transformations on both the generation as well as consumption side. In the recent past, the first wave of prosumers entering the scene was kicked-off when biomass power stations started to find widespread adoption amongst farmers during the early nineties. Around ten years later a second wave followed when an increasing amount of individuals started investing in photovoltaic systems and erected them on their premises. The development was fuelled by the favorable regulation and maturing technology, also finding expression in dwindling prices for solar panels [18]. Meanwhile, a couple of hundred thousand households have been transformed from mere consumers to prosumers alone in Germany [16].

As the feed-in tariffs are sinking and newer installations are remunerated below the gross electricity price, covering own consumption becomes a new motive for households to erect installations. On that note, prosumers also actively adapt their consumption pattern as a result of the investment made. The prosumers scrutinized deliberately opted for a heating system that essentially consumes electric power instead of oil or gas because their electricity supply is safe and cheap for decades to come. This adaption can be seen as an attempt to capitalize on the advantages of the investment made [19].

Yet, because of the size of the prosumer movement, new societal challenges arise. Since the guaranteed remuneration is above the wholesale price for electric power to be paid at the electricity stock exchange, the question arises of who is going to pay for the difference. Currently, the situation in Germany is such that a partition is paid by all customers of electric power. But as a result, every new prosumer will result in higher electricity prices for the majority of the society. One way of circumventing this predicament of ecology and economics would be a state in which the costs for generating electric power from renewable energy sources are below the market price for electric power, thus, a state of grid parity. Then, investments into renewable energy sources would not necessitate societal support. Further curtailing the feed-in tariffs would abate the rush on renewable energy sources for a short term, as this has been found to be the prime reason for investing in the first place. The importance of dealing with this question, however, underlines how important the prosumer movement and dealing with the resulting challenges has become.

V. IMPLICATIONS FOR THE SMART GRID

The grid and network structure have been erected over several decades, but the transformations taking place in the electric power landscape are about to challenge this structure in mere years. This is highlighted in Figure 2.

In the traditional grid structure power is envisaged to only flow unidirectional from higher to lower voltage levels [12]. However, with increasing distributed generation and local net surplus areas the necessity for bidirectional flows across different voltage levels increases. Therefore, new substations will have to be built in net surplus areas in order to direct the excess reverse flows fed into the low voltage grid into net consumption areas via the medium or high voltage grid. The municipal utility interviewed has emphasized that if no grid fortifications are made or new substations built it cannot guarantee to readily connect further addition of installations without hazarding grid stability.

This context highlights two important matters. Firstly, the smart grid will have to increasingly cater for decentralization, smaller but more volatile and bidirectional flows with the grid development being increasingly sensitive to local circumstances. Thus, the current focus on erecting new lines for bulk transmission across long distances will have to be complemented by grid fortifications on the low and medium voltage level. This is underlined by a second and broader implication: One-sided promotion of single elements is not apt in an electric power landscape where the fine-tuned interplay of distinct elements is paramount to guarantee power stability and reliability. By means of furthering renewable energy sources the prosumers are becoming a system-relevant actor in the power landscape, and so are the flows they feed into the grid. Yet, the grid development is not keeping pace with that development. The current grid structure cannot cushion the volatile and hard-to-predict and steer nature of these flows. Regulations have shown to be decisive; promoting prosumers without fortifying the grid is like incentivizing road traffic without fortifying the roads on the supply chain management side. In fact, by promoting renewable energy sources without adjusting the grid, the grid has become a bottleneck for the trend towards renewable energy sources.

	State	Outlook	Challenge
Renewable energy sources	Aggregated already second highest input share in gross electricity generation	Trend will continue, grid parity is in sight, regulation is key driver	Provision of ample balancing power, development of storage capacity
Distributed generation	Transforming the generation landscape in rural areas, less impact on urban structures	Trend will continue, covering own consumption becomes new driver	Creation of better links between net generation and net consumption areas
Prosumers	Already high number of prosumers, starting to exert market power	Trend will continue, prosumers will become a decisive player	Securement of long-term disposition and better partition of societal costs
Grid / Smart grid	Except for single elements no proper roll-out yet, not keeping pace with development in other areas	Pressure on grid will increase, power quality and stability threatened if the grid is not fortified	Getting promotion and funds, grid fortifications on distribution and transmission level

Figure 2: Findings and implications for the grid

In order to cushion the volatility, both the generation and consumption sides can be targeted. On the generation side, ample balancing power is to be held available at all times. This, in turn, highlights the need for the development of large-scale energy storage capacities. In the absence of these capacities the ability to remotely disconnect generation units becomes a more prominent feature. Currently, all installations having a peak capacity of more than 30kW are to have a remote disconnection switch in Germany. The TSO has highlighted the importance of being able to remotely disconnect installations in order to prevent a grid breakdown if electric power generation surges while demand plummets. With the widespread adoption of these remote switches, single elements of the smart grid have already been rolled out.

The measures possible to tackle the volatility on the consumption side, however, have not been harnessed yet. It has been highlighted throughout the cases that the imminent and significant costs for smart meters are pitted against vague and only long-term benefits and that the brokers were deemed unable to offer the complementary tariffs and dynamic pricing. Yet, the possible overall benefits arising from load shifting simply do not translate into perceptible individual advantages for the customers [20]. Therefore, devices entangled to the smart grid such as smart meters or demand response switches have not found widespread adoption in Germany thus far and require further promotion. If the smart grid is to allow shifting and aligning demand according to generation, a better incentive scheme needs to be created. On the one hand, prosumers could be incentivized to increasingly feed electric power into the grid during total peak demand times and to divert own consumption to off-peak hours by offering premiums. This could help meeting peak demand with renewable instead of conventional energy sources and reduce costly excess and standby capacity. On the other hand prosumers could be incentivized to shift their consumption to when their captive generation unit produces most electric power, e.g. during sunshine hours [13]. This form of load management could help flattening out the spikes of the reverse flows and therefore reduce the volatility.

The problem here is not that the mechanisms of demand response are not mature yet, but that they are not duly promoted. The cases have shown that the prosumers are largely unaware of the existing options or deem the investments into the entangled devices as not having a secure pay off. Furthermore, the brokers were attested as unready to offer the corresponding tariffs. However, if the brokers are not in the position to embark on demand response, a pivotal element of the smart grid comes to nothing and the designated benefits are in vain [21]. Demand response requires more promotion.

VI. Concluding remarks & Future work

Renewable energy sources, distributed generation and prosumers are already shaping the electric power landscape and are still on the rise. The grid development, however, does not keep pace with this development. This thwarts the entire process as well as power quality and reliability. For the policy makers, this means that the current one-sided promotion of renewable energy sources must be overhauled such that the promotion of renewable energy sources goes hand in hand with developing the grid. In light of the technical maturity and sinking costs of the underlying technology many renewable energy sources like photovoltaic systems will reach grid parity with wholesale market prices soon [22]. This can be seen as a signal to end societal subsidies and divert the funds to the grid and network structure development instead, since the grid itself has become the bottleneck for adding new installations drawing on renewable energy sources.

For the requirements of the smart grid this means that decentralization, small scale generation and volatile bidirectional flows will have to be catered for. In order to better handle these flows demand response mechanisms ought to be further promoted and rolled-out. On a more structural level, better linkage of net consumption and net production areas, as well as the development of grid energy storage capacities, remain top priorities.

Expanding the concept of closed-loop supply chains and fitting it to the electric power landscape has helped gain a fresh grip on the electric power sector. The model's dimensions have proved especially helpful in discerning the driving forces that spur the transformation from a traditional to a modern, decentralized electric power landscape. This is summarized in Table 2. The great similarities between supply chain and electric power management go so far as employees of the TSO describing their job with the words of supply chain management, stating that they can be seen as a freight forwarder, a shipping company. In light of the exposed similarities, this paper is to eventually pave the way for cross-industry knowledge exchange from which both industries could benefit.

Table 2: Traditional vs. decentralized electric power landscapes

Dimension	Traditional	Decentralized
Who	Utilities are dominant players	More players and power shift
What	Generation units have high capacities and are very reliable	More volatile generation from small-scale generation units
How	Unidirectional flows, focus on high voltage grid	Multidirectional flows, distribution grid more important
Why (Sender)	Generation is confined to classical utilities	Regulation initiates and supports prosumers
Why (Receiver)	No reverse flows envisioned	Regulation assigns responsibilities to accept and market the flows
When (operational)	Multidirectional flows hardly occur and are negligible	The multidirectional flows require new operational structures and methods
When (strategic)	No need to address multidirectional flows on a strategic level	The multidirectional flows are significant and require strategic action

Future research is to clarify where exactly the knowledge transfer can take place. Additionally, further clarification is needed on how the regulations can be best fine-tuned in order to allow for a smooth transition phase from the traditional to the modern and decentralized electric power landscape. A possibility to test and evaluate this transition is within the

Power TAC framework [23]. Power TAC is an instance of a smart electricity market, where all elements of a smart grid can be modeled and fine-tuned [24]. This is especially helpful as it has been shown that the interplay of a variety of different factors needs to be brought in line in order to safeguard power reliability and grid stability. The road towards decentralization, characterized by renewable energy sources, distributed generation and prosumers is sketched, but the speed at which the road is taken heavily depends on the complementary development of the smart grid.

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