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Nyckelord: 5-7 st Customer interaction, demand response, demand side management, energy arbitrage, frequency reserve	

Förord

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Innehållsförteckning

Sammanfattning

Ett elkraftsystem med en ökande andel förnybara energikällor kräver tillräckligt med flexibilitet. En typ av flexibilitet för framtidens elkraftsystem utgörs av flexibel el-förbrukning. Begreppet efterfrågesvar beskriver användningen av efterfrågeflexibilitet för att tillhandahålla tjänster till elkraftsystemet. För detta syfte måste aktörer på marknaden, såsom elhandlare, nätoperatörer och aggregatorer, utvärdera hur de ska interagera eller utveckla sin nuvarande

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interaktion med elkunder. Denna utveckling studeras från ett nuvarande- och nära-framtidsperspektiv, såväl som från ett mer långsiktigt perspektiv, för att utreda aktörernas strategiska möjligheter.

För en leverantör av efterfrågeflexibilitet är det mest ekonomiska sättet att tillhandahålla flexibilitet på elmarknaderna att delta på flera marknader samtidigt och därmed tillhandahålla multitjänster. Med fokus på de nordiska elmarknaderna utgör det samtidiga tillhandahållandet av energiarbitrage och frekvensreserver den mest ekonomiska marknadsportföljen för en leverantör med tillgångar av lagringstyp. Specifikt är de metoder som utvecklats i den ena delen av detta projekt tillämpliga för en riskobenägen leverantör som syftar till att maximera sin vinst för nästa dag genom att lägga bud på energi- och frekvensreservmarknaderna. Utöver detta, utreder den andra delen av detta projekt elkunders attityder och förväntningar med en kombinerat kvantitativt och kvalitativt tillvägagångssätt för att studera de strategiska möjligheterna för leverantörerna utifrån det kortsiktiga samt det långsiktiga perspektivet.

Den operativa verksamheten hos en leverantör av efterfrågesvar beskrivs genom stokastisk optimering av buden under osäkerhet från priser, temperaturer, beteenden och modellfel. En generell virtuell batterimodell för samtidig budgivning på flera marknader i dag framåt är utvecklad för tre tillämpningar; Termostatstyrda laster (TCL), elektriska fordon (EV) och ett massa- och pappersbruk (PPM). Genom tillämpning av modellerna på elkraftsystem, pris, temperatur och lastdata kvantifieras potentialen och energiflexibiliteten hos de tre studerade lasttyperna. Denna forskning bidrar med beslutsstödverktyg för leverantörer av efterfrågesvar som deltar i energi- och frekvensreservmarknader (FCR-N). Huvudfokus för de utvecklade algoritmerna är att möjliggöra optimala framtida bud för en riskobenägen leverantör av efterfrågesvarunder olika osäkerhetskällor. Dessutom undersöks inverkan av marknadsparametrar såsom ledtid och avtalsperiod.

Aktörer som interagerar med elkunder står inför en utmaning i att hantera framtida interaktion med kunder som har väldigt olika uppfattning om hur deras flexibilitet kan göras nyttig. Om vi jämför scenarier för aktörernas framtida interaktion med elkunder med den nuvarande interaktionen, där hushåll och elintensiva industrier idag utgör extremerna, ter sig dagens hantering av hushåll och elintensiva industrier inte speciellt olika längre. Den framtida interaktionen kompliceras av att aktörerna kommer behöva implementera dynamiska element i sina erbjudanden samt integrera ny teknik för information och kommunikation tillsammans med kunderna. För elintensiva industrier kommer integritet att vara en begränsande faktor för efterfrågeflexibiliteten, medan integritet är mer av ett temporärt hinder för integreringen av ny teknik med övriga kunder.

Summary

Power systems with increasing shares of renewable energy sources require sufficient flexibility sources. One source of flexibility for future power systems is constituted by flexible electric loads. The concept of demand response captures

the utilization of demand side flexibility to provide services to the power system. For this purpose, actors on the market, such as retailers, distribution system operators, and aggregators, have to evaluate how to interact or develop their current interaction with electricity customers. This development is studied from a current or near future perspective, as well as from the long-term perspective, to be able to investigate the actors' strategic options.

For a demand response provider, the most economic means of providing flexibility in wholesale electricity markets is to participate in several markets simultaneously and thereby provide *multiple services*. With a focus on the Nordic electricity markets, the simultaneous provision of energy arbitrage and frequency reserves poses as the most economic market portfolio for a demand response provider with storage type assets. Specifically, the methods developed in the first part of this project model a risk-averse demand response provider that aims to maximize its profit on the day-ahead by placing bids on the energy and frequency reserve markets. Furthermore, the second part of this project investigates customer attitudes and expectations with a mixed methods approach, to understand how the actors' strategic options may affect different customers' flexibility.

The operational business of a demand response provider is illustrated by stochastic optimization of day-ahead bids under uncertainty from prices, temperatures, behavior, and model error. A general virtual battery model for simultaneous bidding in multiple day-ahead markets is developed for three applications; thermostatically controlled loads, electric vehicles, and a pulp and paper mill. Through application of the models to power system, price, temperature, and load data, the power and energy flexibility of the three studied load types are quantified. This research provides decision support tools for demand response providers that participate in energy and frequency reserve (FCR-N) markets. The main focus of the developed algorithms is to facilitate optimal day-ahead bids for a risk-averse demand response provider under various sources of uncertainty. Additionally, the sensitivity to market timing, such as lead time and contract period, is investigated.

Actors interacting with electricity customers may have a challenge in managing the future interaction with customers that have very different ideas on how their flexible electricity use will be tapped into. With households and electricity-intensive companies being the extremes among customers, the actors' management of the interaction with the two types is not very different today. At least not when compared to the future scenarios for how interaction with electricity customers may develop. The interaction is complicated by the actors' need to implement dynamic elements in their offers and their need to integrate with electricity customers over new information and communications technology. For electricity-intensive companies, integrity may be a limit to their flexibility, while integrity may be a temporary obstacle for the integration of technology with other customers.

Inledning/Bakgrund

Are you willing to support the integration of renewable energy? But are you willing to pay a higher electricity price for that? If you are willing to contribute to a greener energy supply, but not on the cost of your personal economy, then there may be yet another chance for you to help make a chance towards a greener tomorrow.

We all know that we should shift towards a society of decreasing carbon dioxide emissions. By far the largest source of greenhouse gas emissions is found in the power generation sector. The industry has historically been based on fossil fuels (coal, lignite, oil and natural gas) that offer many short-term benefits such as a high energy density, good predictability and controllability.

The goal of the project

The goal is to use the given resources more efficiently in order to integrate renewable energy without increasing the cost for us as individuals. If we want to facilitate a renewable driven power system, the primary goal must be to synchronize generation and consumption at all times.

How can we as individuals support this goal?

There are several household appliances that consume a significant amount of energy, and that can be shifted to different times without impacting our comfort. Examples are dishwashers, laundry machines, tumble dryers, electric heating or heat pumps and in the future, electric vehicles. Several suppliers are already today labelling these devices with “Smart Grid ready”. That means that when the market will be in place, these devices are able to exploit their inherent flexibility and shift consumption to a more favorable time in order to promote renewable energy integration. Similarly, the electricity use at our workplaces could be shifted. In some cases the appliances are the same as in our households, but in other cases the companies use electricity-intensive machinery that could be used in a more adaptive manner. All these appliances would contribute to a flexible consumption.

How would this work in practice?

Let us suppose you are leaving for work in the morning, around 8.00 h and get back home around 17.00 h. After breakfast, you fill the dishwasher and set it up to run. Instead of starting immediately, the dishwasher would decide by itself when it is most favorable to run, given that it needs to be finished by 17.00 h. This simple change would not impact our personal comfort, and yet have a major impact on power system operation when accumulating all available devices.

There are further appliances that offer even more potential than dishwashers: Residential electric heating alone can be changed by 7.4 GW, which amounts to roughly one third of the total Swedish power consumption.

In order to reach the point where we, as individuals, can contribute to balancing to renewable power system, and help mitigate carbon dioxide emission, we need to have a functioning market. This market is being shaped right now and we need more information about flexibility so that this market can operate optimally, like e.g.:

- How much consumption can you shift to a later or earlier time?
- How much financial compensation do you need to shift your consumption? Is this different for night and daytime? (time dependent elasticity)
- When do you want your dishwasher, laundry machine, dryer, etc. to be finished?
- If you don't know, then: When will you know when you will need it?
- When will you use your electric vehicle next?
- What is your temperature comfort zone at home?

Our research provides insights into the time dependent elasticity of consumers. We investigate both the willingness (behavioral economics) and the capability (technical) of consumers to react to incentives from the system operator, and thus help to integrate renewable energy.

The project has for five years financed the research of two doctoral candidates, Lars Herre at the Royal Institute of Technology (KTH) and Tommy Kovala at Mälardalen University (MDH), and joint interdisciplinary collaboration facilitated by both academies and Forskarskola Energisystem (FoES).

Genomförande

The general methodology is illustrated by Fig. 1. KTH was developing optimization models, running simulations, and analyzed the results from a techno-economic perspective. MDH was designing questionnaires to obtain consumer preferences to be used in the models, and interpreting the results from a socio-economic perspective.

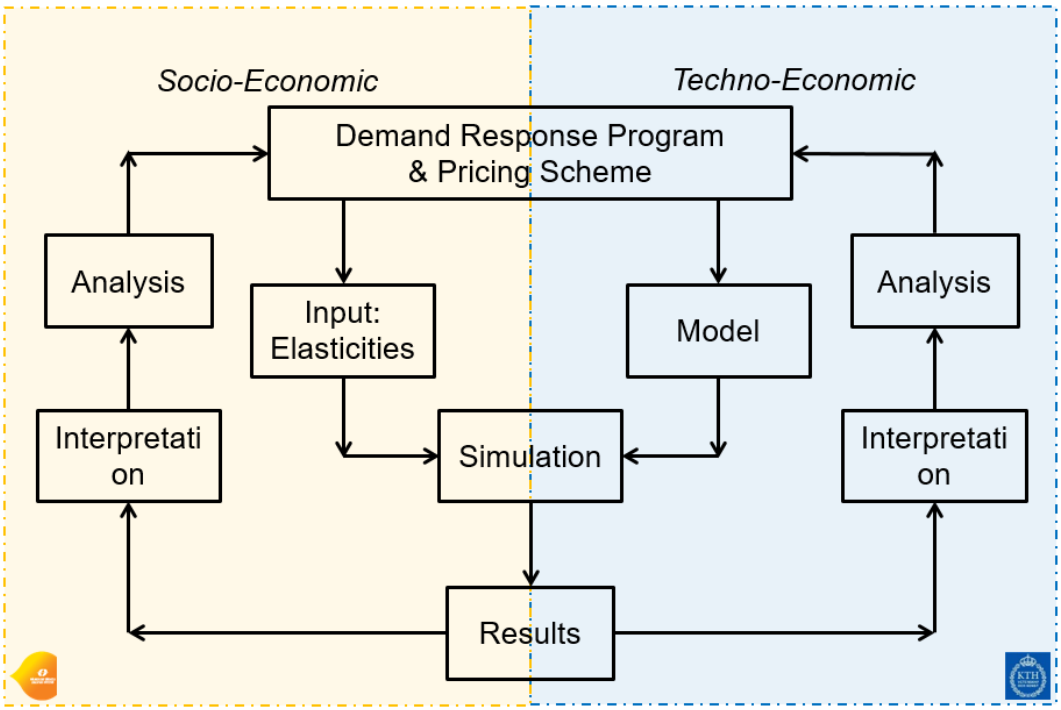

Figure 1 Interdisciplinary Research Methodology

At KTH, five Master students were supervised within this project, some of them worked in collaboration with the aggregator startup Tibber and the company Holmen. The main methods include data analysis (of wind power forecast uncertainty), optimization (of the day-ahead bidding problem of an aggregator) and control (of small scale decentralized demand side resources). The methods used and research conducted is best described through the doctoral thesis [H21].

Customer-near research

At MDH, the customer-near research in the project was mainly driven by Tommy Kovala (PhD candidate), working closely together with a number of supervisors and collaborators over different papers; Cecilia Lindh (main supervisor), Fredrik Wallin (co-supervisor), Emilia Rovira Nordman (co-supervisor), Christos Papahristodoulou (initial main supervisor), Lennart Haglund (co-writer).

Preliminary research exploring research gaps for cooperation and interaction with customers on energy markets is described in [K1, K7-K8]. Conceptual research exploring gaps in research on future interaction on the electricity market was carried out through literature reviews presented and explained in [K3-K4]. Empirical research was carried out through collecting survey responses from

households, described in [K5], through analyzing survey responses already collected by Lennart Haglund, described in [K2], and through qualitative interviews with households and companies [K6]. The research process and conclusions will be further elaborated in the forthcoming doctoral thesis [K9].

Resultat

Demand response has a vital role to play in providing flexibility to future power systems with high shares of variable renewable energy sources. For a demand response provider (DRP), the most economic means of providing flexibility in wholesale electricity markets is to participate in several markets simultaneously and thereby provide multiple services.

This project investigates the need for, exploitation of and potential from DRPs providing multiple services. Specifically, it models a DRP that aims to maximize its profit on the day-ahead by placing bids on the energy and frequency reserve (FCR-N) markets. Based on a review of Nordic electricity markets, the frequency containment reserve (FCR-N), i.e., primary frequency reserve market is shown to present an attractive business case for a risk-averse profit-maximizing DRP.

To capitalize on load flexibility, a general virtual battery model for simultaneous bidding in multiple markets is developed for three applications; thermostatically controlled loads (TCL), electric vehicles (EV), and a pulp and paper mill (PPM). The models can be used to assess the flexibility potential that a DRP can provide in a market-based procurement of energy and reserves. Through application of the models to the Swedish power system, price, and load data, the flexibility of the three studied load types is quantified in terms of power, energy, and FCR-N capacity.

The key conclusions of this project and of the associated publications are summarized below:

- There is a need for more flexibility in future power systems based on variable renewable energy sources.
- Today, the FCR-N market allows for the participation of DRPs (if prequalification tests are passed). A DRP offering flexibility in energy and FCR-N markets shows an improved business case compared to the traditional retailer role.
- A conservative estimate of the mean FCR-N potential from flexible loads in Sweden today yields more than 2 GW/0.1Hz. The Swedish TSO currently only procures 240 MW/0.1Hz for each hour. Thus the flexibility need in terms of FCR-N can be theoretically satisfied by controllable loads whose flexibility is harnessed by Demand Response Providers (DRPs).
- A DRP providing FCR-N can reduce the balancing cost of the system operator. Recently, the balancing cost in FCR markets has increased significantly.

- Short market timing, i.e., late gate closure and short contract periods, are favorable for harvesting flexibility from demand side, both in terms of power/energy capacity and in terms of the profitability of the DRP.
- The potential of demand side flexibility is expected to grow with the increased use of electric vehicles.

Customer-near research

The purpose for this research was to contribute with knowledge on how electricity market actors can affect their relationships with electricity customers. My investigation model implements perspectives from traditional research topics for research on business strategies and marketing (the adoption of ICT; the adaptation of business models) through investigating interaction between electricity market actors and electricity customers. The investigation takes a theoretical stance in assuming that the interaction between the actors and electricity customers takes place partially to develop the business relationship between the two actors, and that it supports efforts put into influencing electricity customers to become more flexible.

The conceptual research is an investigation of scenarios for electricity companies where they would benefit from changed interaction patterns with electricity customers and the role ICT will play in facilitating the interaction. The conceptual research explores two knowledge gaps in previous research on how electricity companies' interaction with electricity customers may have to change in order to meet the challenges of the transforming business environment. The first gap, on the impact of lead time for market information was studied interdisciplinary as described above. The conceptual research was based on a tabulation of results from DR pilot research projects implicitly studying different information lead times. The second gap research was more generally studying how dynamic pricing impacts interaction between business parties. The conceptual research was based on a review of how interaction has been studied in the context of dynamic pricing, such as in the case of Uber.

The empirical research investigates electricity customers' attitudes and perceived needs from business relationships with electricity companies, as well as electricity customers' intentions to adopt new practices related to the supply and use of electricity and reasons to why customers' intentions may change. Swedish households and electricity-intensive companies were studied with different questionnaires, where 122 electricity-intensive companies' views on their supply relationships had been collected in another project (Haglund, 2019). Both questionnaires were analysed quantitatively, and to triangulate various customers' perspectives on their future interaction with electricity companies, interviews were carried out with a few households and a larger group of companies. This mixed methods approach was used to be able to more closely categorize customers in order to understand the strategic options electricity companies can use to tap the potential for flexible electricity use.

Questionnaire responses, on the interaction for supply and use of electricity, from 283 households and 122 electricity-intensive companies were analysed to describe electricity customers' views on their relationships with electricity market actors. Furthermore, to understand the customers' intentions to cooperate with the actors and expectations on their future electricity use, 5 households and 55 companies were interviewed.

The investigation proposes the following conclusions:

- The first conclusion is that electricity market actors may have a challenge in managing the future interaction with customers that have very different ideas on how their flexible electricity use will be tapped. With households and electricity-intensive firms, being the extremes among customers, the management of the interaction between the two types is not very different today, at least not in Sweden where smart meters are widely deployed. Furthermore the current management is not that different when compared to future scenarios for interaction where ICT is used by actors to automatically control loads. The main difference in future management of and interaction with customers will likely be based on the share of electricity use that is flexible, how available that share is, and to what price.
- Based on conceptual research, a more in-depth analysis of the scenarios for future interaction between electricity market actors and electricity customers is that short information lead times and increased dynamics in pricing require highly interdependent actors to generate higher shares of flexibility for each customer. The high interdependence comes from ICT and automation being implemented on a detailed level into the customer's everyday practices, as well as the actor being very reliant on frequent interaction to get the data required. To get the most out of customers' potential flexibility, actors may integrate with the customer's everyday practices through automated data transfers and control of specific loads. The ideally integrated customer, where the majority of electricity use is flexible and controllable for the external actor, is more likely to be a household or possibly a smaller company. This conclusion is mainly based on the high availability of loads such as electric heating, other thermostatically controlled loads, and electric vehicles.
- Based on the empirical research, the conclusion is that even though customers are very different, the interaction and service is not that different. Electricity market actors do not have a significant strategic role in the implementation of ICT for most customers, neither do they have much interaction with most customers, except for when explicitly demanded by the customer. The exception to the rule are the electricity-intensive firms, or at least some of them, which already interact with electricity market actors on more complex energy services and sometimes even on flexible use of electricity (extrapolation to cases outside the empirical study). The interaction on more complex services seem to take

place if trust has been developed between the parties. This trust could be developed rather quickly due to an interaction-intensive start to the business relationship to establish suitable price securing measures. However, since the need for flexible electricity use is low currently, these firms' current potential is most often not utilized. However, increasing use of more electricity-intensive companies' potential for flexibility is limited by their need for integrity in controlling major loads and flexibility to adapt to their own customers' demands.

- Other firms and households, however, may tolerate a higher degree of integration with electricity market actors through ICT. The actors could work with these customers to increase the frequency of interaction and offer ICT "gadgets" to integrate with specific appliances used in everyday practices. Based on the empirical research, households are mainly considering their electricity use during late afternoon and evening hours to be especially valuable, currently and not including a high share of electric vehicles. Furthermore, about 20-40 % (span based on multiple questions and non-responding households) of studied households considered not accepting automation of loads in their homes, if not receiving relevant information or any mandate to be able overrule the control.

Diskussion

It should be noted that the developed optimization and control problem formulations assume the DRP is a price-taker, i.e., the bid volume and price are not effecting the market-clearing. This assumption holds well for a relatively small market participant. The larger the market share of the DRP, however, the more the market clearing will be impacted by the DRP's decisions. This means that a DRP that offers flexibility in a profitable market would slowly take away its own business case by lowering the price incentives in that market with increasing market share.

One major challenge for aggregators is the trade-off between model accuracy and computational tractability. With aggregate load models, computational tractability is high, and the number of loads can be easily scaled up. This comes, however, at the cost of model accuracy.

Each type of load has unique properties that may limit its aggregate power or energy capacity offered to the market. For instance, electric vehicles are characterized by a high power rating of the charging station and battery, while the charging duration, vehicle availability, and energy capacity are rather limited. To overcome the shortcomings of specific loads, the combination of multiple types of loads may achieve beneficial portfolio effects.

Besides, the stacking of services can be extended to other ancillary service markets. In this project, the provision of multiple services for energy and reserve

(FCR-N) markets is investigated. If the same capacity is bid into additional ancillary service markets, further revenue streams can be exploited.

Customer-near research

Future work may add to the research presented in this thesis by targeting how the implementation of ICT-"gadgets", with AI control and communication through the internet-of-things (IoT), affects electricity customers' perception of their use of the electricity system. The implementation of such gadgets along with more distributed and visible electricity production may affect the visibility of the electricity use and/or electricity system, and affect electricity customers' engagement in it. The further spread of customers turning into prosumers may add strategic options for electricity customers to engage in micro-grid investments. Improved and better packaged "gadgets" with AI control and IoT communication may allow communities of households and/or firms to share their own electricity production and flexible electricity use directly with each other, and reduce their dependence on electricity market actors. This would refer to a scenario where the actor has no strategic role in the implementation of the ICT, interacts with or serves the community, and has little interaction with the customers.

Another addition to the research on the future interaction between electricity market actors and electricity customers would be to study the benefits for actors specialized on certain types of customers. In the study it is assumed that an actor interacts and does business with both households and electricity-intensive firms, and all of the customer types in between. If instead approaching the challenge of interacting and developing the interaction with its customers, assuming that the actor focuses on a specific type of customer for its business model, the analysis and conclusions might be different.

Publikationslista

List of Journal Publications:

[H1] L. Herre, J. L. Mathieu and L. Söder, "Impact of Market Timing on the Profit of a Risk-Averse Load Aggregator," IEEE Transactions on Power Systems, 2020.

This paper explores the impact of market timing on TCL aggregate power consumption and reserve capacity bids and quantifies trade-offs between market timing and flexibility. We first optimize the power consumption and reserve capacity offers at given lead times and contract periods, varying from 24 hours ahead to real-time. We then introduce uncertainty in prices and TCL availability, formulate a two-stage chance-constrained optimization problem of a risk-averse aggregator, implement it on a rolling horizon basis, and evaluate how the trade-offs change. The results show that shorter lead times and contract periods positively impact TCL profit as well as flexibility if the prediction horizon is sufficiently long. The proposed method can be used by aggregators to decide on optimal bids and incentive payments to consumers to reward flexibility.

[H2] L. Herre, S. Kazemi and L. Söder, "Quantifying Flexibility of Load Aggregations: Impact of Communication Constraints on Reserve Capacity," IET Generation, Transmission & Distribution, 2020.

The quantity of reserves depends not only on the aggregate power capacity, but also on information and communication technology, exogenous parameters, and system operator requirements. Specifically, the practical limitations origin from (i) communication constraints, (ii) ambient temperature, and (iii) the dispatch time of the activation signal. This paper explores the impact of these parameters on the amount of reserves that an aggregator of TCLs can provide to the system operator based on centralized control of a TCL population. We propose a decision support tool that can be used by aggregators to decide on maximum dispatchable reserve bids. The method can accommodate the specific control algorithm and TCL population of an aggregator and is based on offline computation. It constitutes a powerful reserve bid library to be used when optimization tools become computationally intractable due to the increased number of decentralized flexible loads.

[H3] L. Herre, T. Matusevičius, J. Olauson and L. Söder, "Exploring Wind Power Prognosis Data on Nord Pool: The Case of Sweden and Denmark," IET Renewable Power Generation, 2019.

In this paper, I propose a methodology to verify public data with the example of wind power prognosis published by Nord Pool. I focus on Swedish data and identify a significant bias that increases over the forecast horizon. In order to explore the origin of this bias, they first compare against Danish forecast and then describe the underlying structure behind the submission processes of this data. Based on the balance settlement structure, I reveal that Swedish ‘wind power prognoses’ on Nord Pool are in fact rather wind production plans than technical forecasts. I conclude with the recommendation for improved communication and transparency with respect to the terminology of public data on Nord Pool. I stress the importance for the research community to check publicly available input data before further use. Furthermore, the root-mean-square error and the spatio-temporal correlation between the errors in the bidding areas at different horizons are presented. Even with this compromised data, a stronger correlation is identified in neighbouring areas.

[H4] I. Dimoulkas, P. Mazidi and L. Herre, "Neural networks for GEFCom2017 probabilistic load forecasting," International Journal of Forecasting, vol. 35, no. 4, pp. 1409-1423, 2019.

This report describes the forecasting model which was developed by team 4C for the global energy forecasting competition 2017 (GEFCom2017). The model is based on neural networks. Temperature scenarios obtained from historical data are used as inputs to the neural networks in order to create load scenarios, and these load scenarios are then transformed into quantiles. By using a feature selection approach that is based on a stepwise regression technique, a neural network based model is developed for each zone. Furthermore, a dynamic choice of the temperature scenarios is suggested. The feature selection and dynamic choice of

the temperature scenarios can improve the quantile scores considerably, resulting in very accurate forecasts among the top teams.

[H5] L. Herre, F. Tomasini, K. Paridari, L. Söder and L. Nordström, "Simplified Model of Integrated Paper Mill for Optimal Bidding in Energy and Reserve Markets," in Applied Energy, 2020.

In this work, the day-ahead cost minimization of a risk-averse pulp and paper mill is formulated as a two-stage stochastic problem, considering thermodynamic and electrical constraints. The bids in the energy and reserve markets are jointly optimized subject to price uncertainty as well as uncertainty of frequency realization. The results of a case study in Sweden display a significant economic benefit in exploiting the flexibility of integrated pulp and paper mills with electric boilers. The expected cost of the pulp and paper mill resulting from different strategies are compared and the risk-aversion of the pulp and paper mill is investigated. Reserve offers are mainly facilitated by fast-acting electric boilers and supported by flexibility in the steam network. We show that reserve offers can significantly improve the profitability of the pulp and paper mill.

[H6] L. Herre, B. Nourozi, M. R. Hesamzadeh, L. Söder and Q. Wang, "Provision of Multiple Services with Controllable Loads as Multi-Area Thermal Energy Storage," under review in IEEE Transactions on Power Systems.

Based on a performed survey of Swedish single- and two-family dwellings with electric heating, this paper quantifies the potential of TCLs to provide reserves to the power system in Sweden. To this end, dwellings with heat pumps and direct electric heaters are modeled as thermal energy storage equivalents that can be included in a linear two-stage problem formulation. We approach the operational flexibility of the TCLs by modeling a risk-averse aggregator that controls decentralized TCLs and aims to maximize its own profit. The results show a potential of 2 GW/0.1 Hz averaged over a year, and up to 6.4 GW/0.1 Hz peak capacity.

[K1] T. Kovala, F. Wallin, and A. Hallin, “Factors influencing industrial excess heat collaborations”, Energy Procedia, vol. 88, pp. 595-599, 2016.

Analysing factors leading to successful collaboration between industrial companies and district heating companies. The analysis was based on data from 25 qualitative interviews and a quantitative survey including 87 companies involved in industrial excess heat collaborations. The data was collected by students in a project course. Factors important for a working collaboration were: the economic incentive for the main investor, interest in improving the environmental and local profile from both collaborators, and transparency in the continuous interaction between the collaborators.

[K2] L. Haglund, T. Kovala, and C. Lindh, “Managing complexity through business relationships: the case of the Swedish electricity market”, Int. J. Management and Decision Making, vol. 18, no. 2, pp. 209–227, 2019.

In the industrial market, electricity is an essential resource for production, as a stop in its flow may cause expensive production loss and thus tremendous cost. This strong resource dependence and the inevitable competition that comes with deregulation of the market, makes the electricity business complex and relationships of long-term orientation to form. To study such relationships, a mixed method is applied to provide contextual knowledge: by four interviews and a descriptive model and a structural model with three hypotheses developed (n = 122). Managers of products that may seem simple and traded in a market where low cost prevails should think again - stable relationships are a necessity for rational decisions also in this case, particularly since interdependence is influential.

[K3] L. Herre, T. Kovala, L. Söder, and C. Lindh, “Flexibility Now or Later – Impact of Market Timing on Social Welfare of Flexible Customers”, Manuscript prepared prel. for Energy Policy, 2020.

Demand side management enables flexible electricity consumers to participate in system services that contribute to enhanced integration of renewable energy sources. The specific market timing, pricing scheme and demand response program decide in which way consumers receive and react to incentives. Aside from pricing, several other parameters were found to greatly influence consumer response. Here, the impact of lead time on the flexibility of consumers is investigated and its impact on social welfare is estimated. The price elasticity of consumers can vary in different ways depending on the lead time. Consequently, the time when the price is broadcast would impact the response and the social welfare. We summarize projects and literature on consumer elasticity and conduct a simulation study, where the aggregated demand is updated with statistically improved forecasts at several instances. The results show the importance of lead time for demand side management. We find that the difference between stated and measured elasticity results in a demand flexibility gap and quantify this in terms of social welfare. We conclude that lead time should be considered in electricity market design, e.g., in consecutive ahead markets in order to tap the full potential of flexibility from the demand side.

[K4] T. Kovala, “Dependence on a dynamically priced necessity”, Manuscript being prepared, 2020.

Information flowing into the hands of customers, is one way to look at dynamic pricing, but it may also provide opportunities for the actors to communicate and share data more interactively, such as exemplified by Uber for transportation services. Especially if you could utilize dynamic pricing together with IoT, data sharing could be triggered in either direction, automatically, based on actions motivating it. However, allowing continuous IoT communication with customers’ appliances or automated control of the appliances through IoT “gadgets” is what would be considered an act of high integration of ICT in a business relationship, which is also associated with issues for integrity.

[K5] T. Kovala, “Change of management into Demand Response”, Manuscript being prepared, 2020.

Results from this questionnaire show that households perceive that they take responsibility for how they consume electricity, but they have limited possibilities to actually affect what they get to pay. Whether or not they have great opportunities to consume electricity in a flexible manner, they are seldom incentivised or encouraged enough to act in that way, but if electricity prices temporarily became extremely high, many households would consider using electricity more flexibly even without the help of automation. Many households though would currently refuse automated control of any appliance, even electric heating.

[K6] T. Kovala and F. Wallin, “Money is not the issue: critical voices from Swedish electricity users on demand response”, Manuscript being prepared, 2021.

For electricity market actors’ to analyse their strategic options on the future electricity market, understanding electricity customers’ expectations on electricity use and interaction is important. The study analyses qualitative interviews with 5 households and 55 companies. The interviews sprung from questions on differences expected in their everyday business/living within 10 years, with focus on energy use.

List of Conference Publications:

[H7] L. Herre, "Impact of Imbalance Settlement System Design on Risk-Averse Energy Storage," (in 17th International Conference on European Energy Market, 2020, pp. 1-6.

In this paper, the bidding strategy of a balance responsible party under different imbalance settlement system designs is modeled. Furthermore, the risk-aversion of a balance responsible party managing an energy storage system and the impact on its profitability is studied.

[H8] A. Khodadadi, L. Herre, P. Shinde, R. Eriksson, L. Söder and M. Amelin, "Nordic Balancing Markets: Overview of Market Rules," in 17th International Conference on European Energy Market, 2020, pp. 1-6.

In this paper, we conduct a thorough literature review on Nordic balancing markets and summarize the market rules and requirements. This review can help operators and modelers to better represent the Nordic power system.

[H9] L. Herre, "Risk-Averse Aggregator of Controllable Loads as Virtual Battery Providing Multiple Services," in 17th International Conference on European Energy Market, 2020, pp. 1-6.

In this paper, the day-ahead profit maximization of a risk-averse virtual battery operator providing multiple services is formulated as a MILP. The impact of different battery design parameters on the reserve provision and overall profitability is investigated. We show that power capacity has the highest impact on the profitability and reserve provision of the virtual battery, followed by energy capacity and grid connection limits.

[H10] L. Herre, F. Tomasini and K. Paridari, "Optimal Day-Ahead Bidding of a Risk-Averse Pulp and Paper Mill in the Energy and Reserve Market," in 16th International Conference on European Energy Market, 2019, pp. 1-5.

In this work, the day-ahead cost minimization of a risk-averse pulp and paper mill (PPM) is formulated as a two-stage stochastic problem, considering thermodynamic and electrical constraints of the PPM. The bids in the energy and reserve markets are optimized subject to price uncertainty. The results of a case study in Sweden display a significant economic benefit in exploiting the flexibility of PPM. The expected cost of the pulp and paper mill resulting from different strategies are compared and the risk adversity of the PPM is investigated. We show that reserve

[H11] L. Herre, J. Dalton and L. Söder, "Optimal Day-Ahead Energy and Reserve Bidding Strategy of a Risk-Averse Electric Vehicle Aggregator in the Nordic Market," in 13th IEEE PowerTech 2019, 23-27 June, Milano, Italy, 2019.

Electric vehicles (EV) can be considered as energy storage with availability, energy and capacity constraints that can provide flexibility to the power system in the form of balancing products when aggregated. In this paper, we develop a two-stage stochastic optimization problem that maximizes the profit of a risk-averse EV aggregator for bids on the day ahead in both energy and Frequency Containment Reserve (FCR) markets. Unidirectional charging is examined, while we take into account uncertainty from prices and vehicle availability. Case studies are carried out in different Nordic bidding areas based on historical EV charging data. We identify a strong temporal alignment of EV availability and high FCR-N prices. Results show that consumption is shifted largely towards early hours of the morning. When compared to a reference cost of charging case, up to 50% of the cost of charging can be recovered in Norway, and 100% in Sweden.

[H12] I. Dimoulkas, L. Herre, E. Nycander and M. Amelin, "A hybrid model based on symbolic regression and neural networks for electricity load forecasting," in International Conference on the European Energy Market, EEM, 2018.

This paper proposes a hybrid model for electricity load forecasting. Symbolic regression is initially used to automatically create a regression model of the load. Then the explanatory variables and their transformations that have been selected in the model are used as input in an artificial neural network that is trained to predict the electricity load at the output. Therefore symbolic regression operates as a feature selection creation method and forecasting is done by the artificial neural network. The proposed hybrid model has been successfully used in an electricity load forecasting competition.

[H13] J. Dalton, L. Herre and L. Söder, "Exploring the Business Case of a Risk-Averse Electric Vehicle Aggregator in the Nordic Market," in 2nd E-Mobility Power System Integration Symposium, 2018.

In this paper, we use first hand data of a real EV fleet of Tesla vehicles and their historical driving patterns to develop a two-stage stochastic optimization problem.

This model maximizes the profit of a risk-averse EV aggregator that aims to place optimal bids on the day ahead in both energy and Frequency Containment Reserve (FCR) markets. Only uni-directional charging is examined, while we take into account uncertainty from prices and vehicle utilization. Case studies are carried out modelling individual vehicle driving behavior in different Nordic price areas in both winter and summer. We identify a strong alignment of EV availability and periods of high FCR prices. Results show that consumption is shifted largely towards early hours of the morning. When compared to a reference ”cost of charging case”, up to 50% of the cost of charging can be covered in Norway, while the entire cost is met in Sweden.

[H14] L. Herre, L. Söder and J. L. Mathieu, "The Flexibility of Thermostatically Controlled Loads as a Function of Price Notice Time," in 2018 Power Systems Computation Conference (PSCC), 2018.

This paper explores the impact of energy/AS price notice time, i.e. the time between when the price is announced and when it takes effect, on the TCL energy consumption and AS capacity bids, and quantifies trade-offs between notice time and flexibility. We first optimize the energy consumption and AS capacity offers at a given notice time, varied from 24 hours ahead to real-time. We then introduce uncertainty in TCL availability, formulate the stochastic optimization problem, and evaluate how the trade-offs change. We find that price notice time impacts TCL profits, but does not significantly affect the total AS capacity offered over the day. However, AS capacity offers are impacted by uncertainty, which is likely to increase with notice time.

[H15] I. Dimoulkas, P. Mazidi and L. Herre, "EEM 2017 Forecast Competition: Wind power generation prediction using autoregressive models," in European Energy Market (EEM), 2017 14th International Conference on the, 2017.

In this paper, we propose an autoregressive (AR) model that can be used as a benchmark model to validate and rank different forecasting models and their accuracy. The presented paper was developed within the scope of the European energy market (EEM) 2017 wind power forecasting competition.

[H16] L. Herre and L. Söder, "Enhancing market access of demand response through generation forecast updates," in 2017 IEEE Manchester PowerTech, 2017.

This paper presents a market model of demand response that enhances an efficient use of flexible consumers by hourly updates. The consequences of flexible electricity consumers are studied in a Real Time Pricing model with continuous forecast updates, where elasticity is subject to notice time. A case study is presented using data from Sweden. We conclude that current demand response programs are not optimally designed to integrate consumer flexibility that changes with the notice time.

[H17] L. Herre, T. Matusevičius and L. Söder, "Swedish Wind Power Forecasts: Procedure, Error Distribution and Spacio-Temporal Correlation," in 16th International Workshop on Large-Scale Integration of Wind Power into Power

Systems as well as on Transmission Networks for Offshore Wind Power Plants, 2017.

In this paper, Swedish wind power forecast accuracy over the forecast horizon is analyzed and compared among different bidding zones. The root-mean-square error trajectory over the horizon is shown for Sweden and its individual bidding areas. In addition, a significant systematic wind power under-prediction is identified and discussed. The paper continues to analyze the wind power forecast error distribution with respect to the horizon. Furthermore, the spacio-temporal correlation between the errors at different horizons and bidding areas is presented. As expected, a stronger correlation between the forecast errors is identified in neighboring areas.

[H18] L. Herre, T. Kovala, L. Söder and C. Papahristodoulou, "A Study on the Flexibility of Electricity Consumers for the Swedish Context: Modelling, Quantification and Analysis of Notice Time," in Swedish Association for Energy Economics conference, 2016.

In this paper, the impact of notice time on the flexibility of consumers is investigated. We summarize projects and literature on consumer elasticity and conduct a simulation study. The results show the significance of notice time dependent elasticity of consumers on power balancing in forward markets.

[H20] L. Herre and L. Söder, "On the flexibility of electricity consumers: Introducing notice time," in 13th International Conference on the European Energy Market (EEM), 2016, pp. 1-5.

This paper presents a review of existing demand response programs and reflects on consumers' flexibility with respect to notice time. While some schemes include fixed notification schedules, others allow for variable notice time, or even continuous updating. In this paper, the consequences of notice time and update intervals on flexible electricity consumers are studied in Demand Bidding model with continuous forecast updates.

[K7] Wallin, F., Torstensson, D., Kovala, T., & Sandberg, A. 2016. "Using an energy intervention framework to evaluate enduser willingness to participate in demand response activities", 2016 IEEE Power and Energy Society General Meeting, 17-21 July 2016, Boston, MA, USA.

This paper describes the results from implementing an energy intervention framework, a novel method to evaluate consumers' willingness to participate in demand-response actions. An energy intervention scenario encouraged consumers to change consumption behaviour during peak hours in December. Consumers' participation was measured through a web-based survey as well as using smart meter data. The study included 528 consumers divided into three groups: i) participation with economic compensation; ii) participation without economic compensation; and iii) control group. In total 106 households responded to the survey, 53 stated that they actively took part in the energy intervention. When analysing smart meter data it was evident that the groups that had received the intervention and confirmed their participation had lowered the load compared to

the control group by 19%. The monetary incentive did not have a positive effect on either participation rate or reduced consumption. None of the participants claimed the economic compensation.

[K8] Kovala, T. (2016) “Deciding about electricity usage: A thesis on market incentives to steal focus from electricity consumers”, presented at PhD Workshop at the 4th Scandinavian Conference on Industrial Engineering and Management (ScAIEM), 28-30 November 2016, Luleå, Sweden.

In this thesis proposal presented at the PhD Workshop, the purpose presented was to analyse the ways residential electricity consumer-behaviour can be changed, depending on the setup of the Demand Response program implemented in the electricity market, and in turn predict the potential flexibility of consumers in Swedish electricity system context. The analysis was supposed to contribute to the development of consumer behaviour research for markets connected to infrastructural systems, with its focus on market setup parameters beyond market price, specifically incorporating multiple aspects of time.

Theses:

[H21] L. Herre, "Demand Flexibility for the Simultaneous Provision of Multiple Services - Tapping the Potential of Controllable Electric Loads for Frequency Reserves and Energy Arbitrage," Doctoral thesis, Stockholm, Sweden: KTH Royal Institute of Technology, TRITA-EECS-AVL-2020:35, ISBN: 978-91-7873-569-3, 2020.

Conclusions described in the result section above.

[K9] T. Kovala, “Including or integrating customers – a study of how interaction with electricity customers may change in a future renewable electricity system”, Doctoral thesis, Västerås, Sweden: MDH Mälardalen University, Manuscript being prepared for defense in 2021.

Current conclusions described in the result section above.

Referenser, källor

L. Haglund, “Affärsrelationer på den svenska elmarknaden”, Licentiate thesis, Västerås, Sweden, MDH Mälardalen University.

Bilagor

Administrativ bilaga.

[K1, K2, K7, H18] are appended to this document.

[K8] is fully available on http://mdh.diva-portal.org/. [H1-H17, H19-H21] are fully available on https://kth.diva-portal.org/. [K3-K6] manuscripts are still being prepared. [K9] thesis manuscript is still being prepared and will after the defence be available on http://mdh.diva-portal.org/