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Interaction of DSO and local energy systems through network tariffs

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***Abstract*—One crucial factor that influences distributed energy resource investments and operation is the grid tariffs. If the price signal passed on to the consumer is not representative of the actual impact of the decentralized decisions on the power system, we may get inefficiencies. The main problem considered in this research is the interaction of a network operator and consumers to study how grid tariffs should be designed to facilitate favorable decentralized decisions. An equilibrium model based on tariffs is developed and benchmarked against a system optimization to study the effect of capacity-based and volumetric grid tariffs when the grid costs are a function of the decentralized decisions. The results show that both a volumetric and capacity-based tariff scheme provides a suboptimal outcome compared to the system optimal solution. Suboptimal decentralized decisions in the perspective of the overall power system is a result of the tariff schemes not being able to represent the actual network costs. Based on the findings, more innovative tariff schemes or related market mechanisms are needed to facilitate decentralized decisions that are aligned with the costs and benefits for the overall power system.**

***Index Terms*—Network tariffs, bi-level optimization, distributed energy resources, incentives.**

I. INTRODUCTION

Buildings are becoming an increasingly active part of the power system due to the introduction of generation assets at the consumer level and utilization of demand-side flexibility. These changes can be attributed to cost decreases of technologies such as photovoltaics (PV) and promotion of energy efficient buildings with distributed generation through policies such as the EPBD [1]. In light of these changes, it is essential to consider if current regulatory frameworks supports decentralized decisions that are also optimal for the overall power system.

One crucial factor that influence distributed energy resource (DER) investments and operation is the grid tariffs. The grid tariff structure is usually decided by the regulator and the rate is determined by the distribution grid operator (DSO). In most countries, DSOs are monopolies with the objective of recovering their costs within specified limits determined by the regulator. However, if the price signal passed on to the final consumer is not representative of the actual system costs of the decentralized decisions, we may get inefficiencies. For example, if the grid tariffs do not provide a good representation of the network costs, consumers may over-invest in DER to an extent that requires costly grid upgrades. Such behavior could arguably be avoided if the grid tariffs appropriately represent the real upstream cost of the decentralized decisions since the consumer then would consider the actual cost for the rest of the power system and adjust investments and operation accordingly. The value of DER is site and time-dependent as argued by [2] and according to [3] which provide a review of system costs for PV integration, a "generalized cost" cannot be obtained.

To address DER deployment and consumer flexibility, two main modeling approaches can be used: System optimization and decentralized equilibrium. In a system optimization approach such as [4], one optimization problem is formulated for the entire system under consideration, and the optimal investments and operation of DER is calculated. On the other hand, in a decentralized approach, it is recognized that the individual market participants do their optimization based on the information available to them (energy prices, grid tariffs). Therefore, the result from a decentralized approach may have higher total costs compared to a system optimization if the price signals are not a perfect proxy of the upstream costs.

The main inspiration for this paper is [5] which consider sunk cost recovery through grid tariffs for active and passive consumers in a game theoretic equilibrium model. Many interesting observations are made regarding the adverse effects of non-cooperative behaviour. Furthermore, [6] propose a mathematical framework that considers PV investment and operational decisions under volumetric and capacity network tariff schemes in a decentralized approach benchmarked against a central planner optimization. However, in these papers, the total network costs are not dependent on decentralized decisions. In contrast to the sunk cost approach, we consider the case that grid costs are a function of the decentralized decisions made by individual consumers.

The main contribution in this paper is an assessment of the interaction between a DSO and consumers in a game theoretic setting. Furthermore, we assess the impact of imperfect local information at the distributed level when total grid costs are a function of the decentralized decisions. A structure with consumers interacting with the DSO through network tariffs is modeled using a bilevel equilibrium approach. The equilibrium model is benchmarked against a system optimization where all investment and operational decisions are made centrally to minimize total costs.

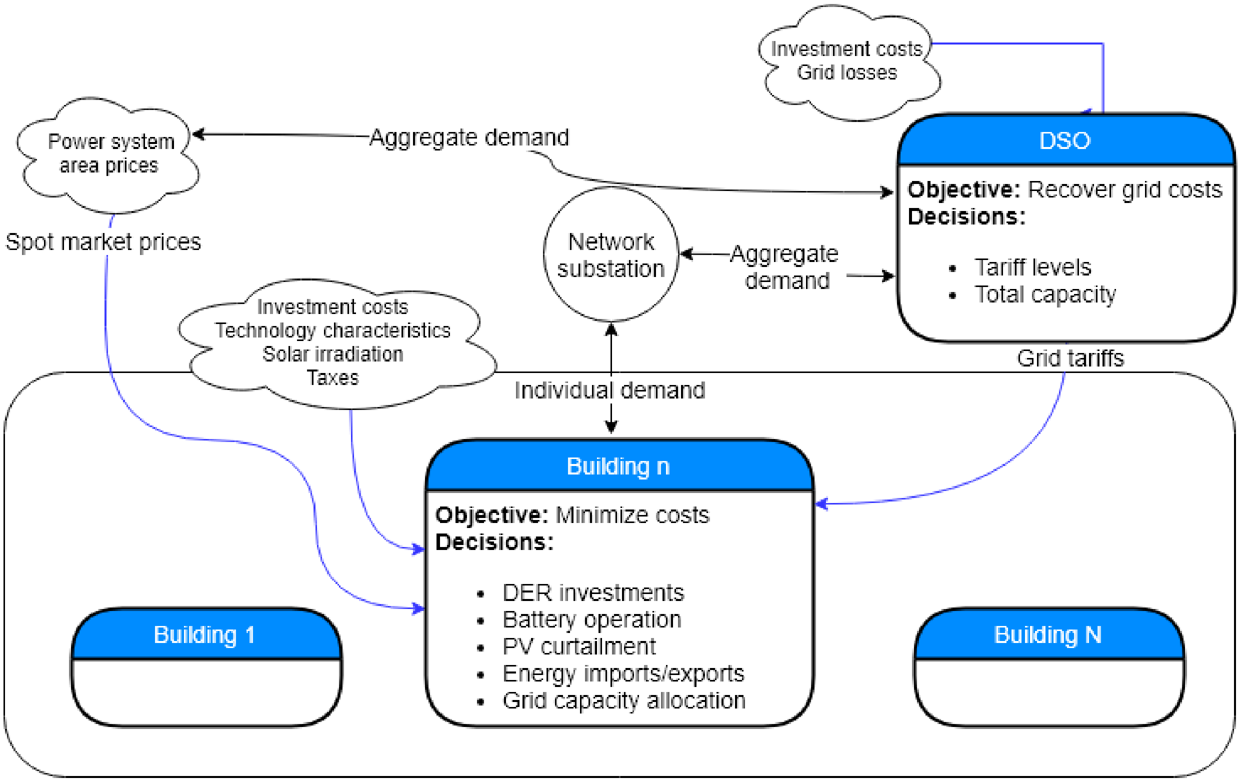

Fig. 1. Schematic of the modeled system

II. METHODOLOGY

The findings are based on a mathematical model that is under development. The model used for this paper is is implemented in Julia for Mathematical Optimization (JuMP) [7]. In this paper we provide a conceptual description of the model features while details can be obtained from [8].

A. *System description*

We consider a system where buildings and a DSO interact according to Fig. 1. The role of the DSO is to connect individual buildings to the power market. For simplicity, we consider the case that one or more buildings are connected to the same node in the network with resulting total network usage according to the sum of buildings connected.

The structure of this model is a bilevel Stackelberg game [9] with multiple followers, where the DSO is the leader, and the consumers are the followers. The interaction between the DSO and the buildings is through network tariffs.

B. *DSOs problem*

The leader in the bilevel game is the DSO which sets the network tariffs that are applied to the consumers in the lower level. The role of the DSO is to build and maintain infrastructure connecting consumers to the power market. Our formulation considers the case where the interconnection capacity for an area is to be decided, and therefore the DSOs costs is a function of the decisions on the lower level. Since we consider the case of an area with new demand, our model does not include sunk costs. Sunk costs could easily be included through a fixed network tariff, but such a fixed tariff would not influence the investment and/or operational decisions and is therefore omitted for simplicity.

The DSOs decision variables are the network tariffs which are set to recover the costs. We consider two types of tariffs: volumetric (EUR/kWh) and capacity-based (EUR/kW).

C. *Consumers problem*

The consumers minimize their annualized investment costs and operational costs for one year.

$$Cost_c = Cost_c^N + Cost_c^{PM} + Cost_c^T + Cost_c^G \qquad (1)$$

Equation (1) describes consumer costs, which include investment costs ($Cost_c^N$), energy costs ($Cost_c^{PM}$), taxes ($Cost_c^T$) and grid costs ($Cost_c^G$). The latter term is influenced by the grid tariffs that are treated as parameters in the consumer problems. The buildings have load profiles that need to be covered by either purchase of power from the power market (subject to grid tariffs) or investments in PV generation assets. The consumers also have the possibility of temporal shifting of their load through battery investments.

D. *System optimization vs. equilibrium solution*

Two model structures are considered: A system optimization and a bilevel equilibrium. The system optimization structure serves as a benchmark and means that all decision variables, both at the building and DSO level, are assumed to be controlled by one entity. Furthermore, system optimization means that the problem is formulated as one optimization problem minimizing total costs in (2). The system optimization approach do not consider grid tariffs since costs both at the DSO and consumer level are included directly.

$$Cost_{tot} = Cost_{DSO} + \sum_{c=1}^{C}(Cost_c^{I} + Cost_c^{PM} + Cost_c^{T}) \quad (2)$$

We formulate the same system as a bilevel game since it is not realistic to assume that all decisions are made centrally in the real world. In this formulation, the buildings do their optimization based on the local information available to them. Specifically, this differs from the system optimization because the network costs are represented by the network tariffs, which are not a perfect representation of the actual network costs. Therefore, the total costs of a bilevel formulation will usually be higher than for the system optimization, except in the case of a perfect tariff scheme.

E. Solution procedures

For the system optimization, all costs according to equation (2) are included in one objective function subject to constraints both at the building and DSO level.

For the bilevel equilibrium, several solution approaches are possible. The model can be formulated as a mathematical program with equilibrium constraints (MPEC) [10], which would be suitable in the case of a DSO pursuing an optimization problem since the DSO would need to take into account the effect its decisions have on the lower level problem. However, our model only considers the case that the DSO needs to recover the costs according to specific rules. Besides, the MPEC formulation would be a nonlinear and nonconvex problem, limiting the tractable problem size. Therefore, we design a solution procedure that iteratively finds the tariffs as outlined in Fig. 2. A significant advantage of the chosen solution procedure is that the consumer problems can be solved independently within each iteration. The decomposition of individual building problems means that the computational burden scales linearly to the number of buildings since each building added to the model only implies solving one additional optimization problem.

III. CASE STUDY

A. Input data and assumptions

In this paper, we consider buildings that are connected to the same network node as visualized in Fig. 1. Since this is a stylized example to investigate DSO interaction between consumers and a DSO, we focus on constructing a case that highlights the effect of decentralized decisions. This section will briefly explain the data that has been used to construct the example. An overview of the parameters can be found in table I.

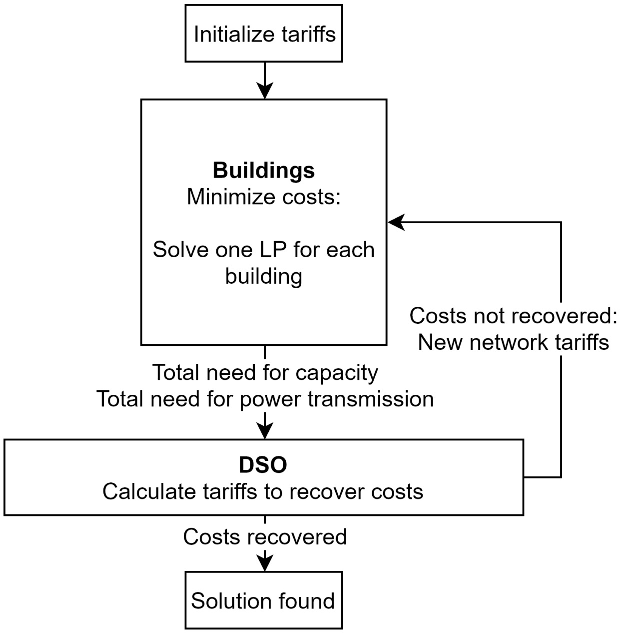

Fig. 2. Outline of bilevel solution procedure, inspired by [5]

TABLE I
INPUT PARAMETERS

Parameter	Value
Network capacity cost	60 EUR/kW/year
Power system losses	6% of transferred energy
Market price	Spot prices 2016 for area NO1
Building demand	Hourly load profiles for 2016
Electricity tax	0.016 EUR/kWh
PV investment cost	13 EUR/kWp/year
PV system losses	14%
Battery investment cost	20 EUR/kWh/year
Battery capacity factor	0.50 kW/kWh
Battery self-discharge	0.1 %/h
Battery converter losses	2%

Network costs: The cost of upgrading network capacity varies from feeder to feeder and therefore can take many different values. In [11] they found that the value of network deferral can be as large as 60 USD/kW-year in the case of a saturated feeder. Our case of building precisely the necessary amount of network capacity is similar to the situation with a saturated feeder, and based on this we assume an annualized cost of 60 EUR/kW for network capacity expansion. In line with [12], the network losses have been set to 6%.

Market Data: Power market prices for the year of 2016 are gathered from Nord Pool spot [13]. In addition to the market price, the consumers also have to pay a tax according to [14] for power purchases. We do not include any tax on energy exports from the buildings.

Building data: We use metering data from 10 residential buildings in southern Norway. The buildings have the opportunity to invest in PV capacity and batteries to shift their load in time.

PV costs have dropped and are expected to continue to do so. According to [15] we can expect costs in the range of 120-210 EUR/kWp in the year 2050. Based on this, we assume a cost of 165 EUR/kWp annualized with a 5% interest rate over 20 years. PV generation data (in kWh/kWp) with a temporal resolution of 1 hour for the location of the buildings in southern Norway has been obtained from the tool PVGIS [16] assuming system losses of 14% related to the PV system and inverter.

Batteries from electric vehicles can be repurposed for stationary use at a lower cost. Although costs and performance characteristics of repurposed batteries are uncertain, we have assumed 200 EUR/kWh based on the findings in [17], annualized with a 5% interest rate over 10 years.

It should be noted that the costs for PV and batteries have been set quite low in our case study to highlight the effect of decentralized decisions in a scenario where DER are profitable.

B. Results and discussion

The models co-optimize investments and operational decisions. Investments can be local in the form of batteries and PV at each consumer or system related in the form of grid capacity. It should be noted that the results are highly dependent on our assumptions and that our primary interest is the comparison of the cases to relate decentralized decisions based on tariffs to a system optimal solution, not the numerical results for any individual case. We carry out a case study for four different situations to assess the impact of decentralized decisions on the system:

1) System optimization: Decisions at the DSO and consumer level are controlled directly to minimize total costs.
2) Equilibrium with capacity-based tariff: Consumers minimize costs subject to capacity-based network tariff determined by the DSO.
3) Equilibrium with capacity-based and volumetric tariff: Consumers minimize cost subject to capacity-based and volumetric tariffs determined by the DSO.
4) System optimization with fixed PV and battery capacities: Decisions at the DSO and consumer level are controlled directly to minimize total costs. Investments in PV and batteries are fixed according to case 3).

System optimization vs. equilibrium: We now compare the system optimization in case 1) with cases 2) and 3), which are equilibrium solutions of the same system. Case 2) has a capacity-based tariff only while case 3) has both a volumetric and capacity-based tariff to represent the network costs. Table II compare characteristics for cases 1) to 3).

TABLE II
DIFFERENCE BETWEEN SYSTEM OPTIMIZATION AND EQUILIBRIUM

	1): SO	2): EQ	3): EQ
Volumetric tariff [EUR/kWh]	NA	NA	0.001547
Capacity-based tariff [EUR/kW]	NA	66.23	60.00
Total costs change [%]	0	+12.9	+12.7
Imports change [%]	0	+0.21	-5.70
Consumer exports change [%]	0	+35.01	+17.34
PV generation change [%]	0	+20.94	+18.87

The system optimization serves as the benchmark since it has the lowest possible total costs. At first glance, we see that the total costs increase by almost 13% when we use the equilibrium approach compared to system optimization. The increase in total costs is a result of the non-cooperative pursuit of a cost-minimization goal at the consumer level with an imperfect network tariff. It can be observed that the total amount of energy that is exported increased by 35% in the case of a capacity-based tariff, but only a 17% increase is observed in the case of both a volumetric and capacity-based tariff. Compared to case 2, the tariff scheme applied in case 3) increases the profitability of self-consuming energy inside the boundary of the individual building since any exchange with the grid are subject to a volumetric tariff. The volumetric tariff acts a transaction cost for trading with the grid, disincentivising such trading. Therefore, the volumetric tariff explains the significant decrease in imports and exports while PV generation is only slightly affected due to the increase in self-consumption.

Investment decisions for the different cases can be found in Fig. 3 and cost characteristics can be found in Fig. 4. In general, the equilibrium model over-invest in the local resources (PV and batteries) compared to the system optimal solution. Also, more interconnection capacity is necessary as well which seems counter-intuitive since it should be possible and beneficial for the system to decrease the interconnection capacity with the increased amount of local resources. However, the explanation for the increase in total interconnection capacity despite the increase in local resources is that the tariffs do not convey information about the coincidental peak to the consumers since the capacity-based tariff only depends on the peak of the individual consumer. The root of this problem lies in the fact that the capacity-based tariff is flat over the year, and therefore do not communicate any time-dependent information about the scarcity of grid capacity.

Optimal operation of suboptimal investments: The increase in total capacity for the equilibrium cases motivated case 4). In case 4), we fixed the PV and battery capacities according to the results in case 3) to see what a system optimization would do with the predetermined amount of local resources. It can be observed that the system optimization with fixed decentralized capacities is able to decrease the amount of interconnection capacity below the equilibrium solution, and even below the previous system optimal solution as well. The decrease below the previous system optimal amount of interconnection capacity is that the increased amount of batteries makes it possible to reduce the grid load even more. It should be noted that case 4) has higher total costs than case 1) since we fix the PV and battery capacities at a suboptimal level. In other words, it would be better to reduce the amount of DER and increase the grid capacity to some extent. Case 4) highlight that the equilibrium solution in cases 2) and 3) provide not only suboptimal investments but also a suboptimal operation of the system since a system optimization can perform better with the same amount of decentralized resources.

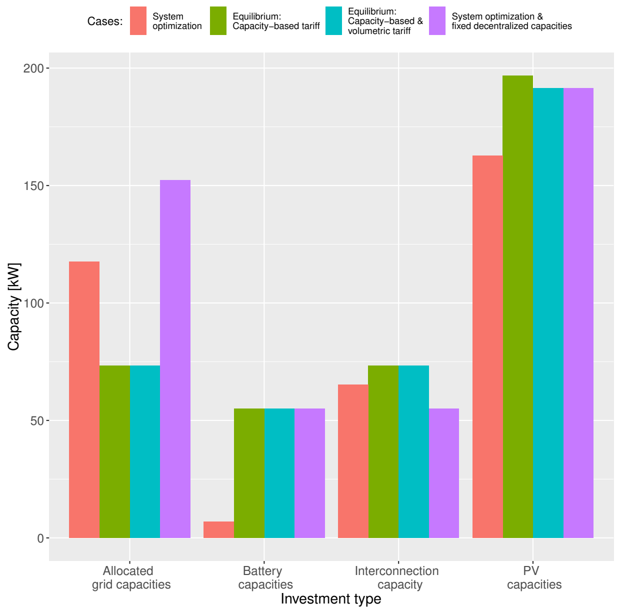

Fig. 3. Investments in capacities for four different cases

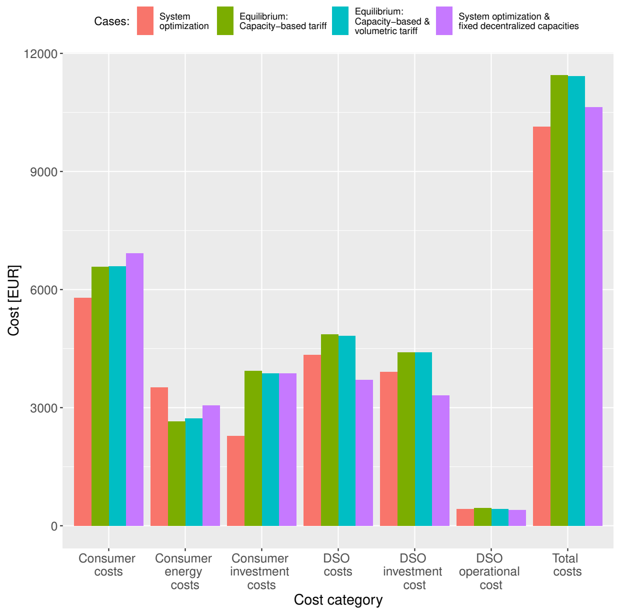

Fig. 4. Detailed cost characteristics for four different cases

Grid utilization and coincidental peak: An interesting observation is that the allocated grid capacities are higher in the system optimization than in the equilibrium despite the increased interconnection capacity in the equilibrium cases. The increased allocation of grid capacities can be explained by the fact that they do not happen in the same moment in time in the case of a system optimization due to different load profiles. In the system optimization, the consumers do not consider the allocated grid capacities as a direct cost since the interconnection capacity is only affected by the total coincidental peak of all consumers. The interconnection capacity and total allocated grid capacity is equal in the equilibrium cases because the capacity-based tariff represents a cost to all consumers based on their peak. In the equilibrium cases, the individual peaks of all consumers occur at the same moment in time due to the similarity of the load profiles, power market prices, PV generation profiles and flattening of demand by batteries.

IV. CONCLUSION

In this paper, we have compared a system optimization approach with equilibrium solutions of the same system to study the effect of tariffs on the obtained solution. The system under consideration consists of consumers that are connected to the power market through a DSOs network. A case study was carried out based on metering data from 10 consumers in southern Norway.

Our results show that an equilibrium solution using volumetric and capacity-based network tariffs increase the total system costs compared to a system optimal solution. One reason for the cost increase is because the tariffs incentivizes increased amounts of investments in resources at the consumer level. In addition to the increase in decentralized resources, the batteries are operated in a sub-optimal manner from an overall system perspective. Increased amounts of batteries should be able to reduce the peak load in the system, but this does not happen with the tariff schemes considered. The total costs are increased with decentralized decisions because of the effects of non-cooperative behaviour to minimize individual costs. A prospective solution to overcome the problem of suboptimal decentralized decisions would be to coordinate resources locally at a higher level than individual buildings. Local coordination of resources can be similar to a system optimization, but requires that the coordinating entity has access to information about the impact on the rest of the power system and is able to properly remunerate the consumers.

From a socio-economic view, the tariff schemes studied in this paper do not utilize the resources in the system optimally since the consumers lack information about what the other consumers are doing. Ideally, the tariff scheme should not penalize consumers for having a high load if the total load in the grid is low at that moment in time. Although a system optimal solution theoretically provides the optimal decisions, a decentralized modeling approach is more realistic and is necessary for studying if the system optimal solution is supported through regulations and price signals. Our results show that flat volumetric and capacity-based tariffs are not sufficient to facilitate decentralized decisions that are also system optimal. Tariff design and local price signals are important topics which the authors plan to direct further research.

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REFERENCES

[1] European Commission, "Directive (EU) 2018/844," *Official Journal of the European Union*, 2018.

[2] B. Rogers, J. Taylor, T. Mimnagh, and C. Tsay, "Studies on the time and locational value of DER," in *24th International Conference & Exhibition on Electricity Distribution (CIRED)*, vol. 2017, no. 1, 2017, pp. 2015–2018. [Online]. Available: http://digital-library.theiet.org/content/journals/10.1049/oap-cired.2017.0403

[3] K. A. Horowitz, B. Palmintier, B. Mather, and P. Denholm, "Distribution system costs associated with the deployment of photovoltaic systems," *Renewable and Sustainable Energy Reviews*, vol. 90, no. December 2016, pp. 420–433, 2018. [Online]. Available: https://doi.org/10.1016/j.rser.2018.03.080

[4] Y. Yang, S. Zhang, and Y. Xiao, "Optimal design of distributed energy resource systems coupled with energy distribution networks," *Energy*, vol. 85, pp. 433–448, 2015. [Online]. Available: http://dx.doi.org/10.1016/j.energy.2015.03.101

[5] T. Schittekatte, I. Momber, and L. Meeus, "Future-proof tariff design: Recovering sunk grid costs in a world where consumers are pushing back," *Energy Economics*, vol. 70, pp. 484–498, 2018. [Online]. Available: https://doi.org/10.1016/j.eneco.2018.01.028

[6] N. Vespermann, M. Huber, S. Paulus, M. Metzger, and T. Hamacher, "The impact of network tariffs on PV investment decisions by consumers," *International Conference on the European Energy Market, EEM*, vol. 2018-June, no. 03, pp. 1–5, 2018.

[7] I. Dunning, J. Huchette, and M. Lubin, "JuMP: A Modeling Language for Mathematical Optimization," *SIAM Review*, vol. 59, no. 2, pp. 295–320, 2017. [Online]. Available: http://arxiv.org/abs/1508.01982%0Ahttp://dx.doi.org/10.1137/15M1020575

[8] M. Askeland, "magnuask/EEM-19 v1.0," 2019. [Online]. Available: https://zenodo.org/badge/latestdoi/190200418%0A

[9] H. Von Stackelberg, *Marktform und gleichgewicht*. J. springer, 1934.

[10] Z.-Q. Luo, J.-S. Pang, and D. Ralph, *Mathematical programs with equilibrium constraints*. Cambridge University Press, 1996.

[11] M. A. Cohen, P. A. Kauzmann, and D. S. Callaway, "Effects of distributed PV generation on California's distribution system, part 2: Economic analysis," *Solar Energy*, vol. 128, pp. 139–152, 2016. [Online]. Available: http://dx.doi.org/10.1016/j.solener.2016.01.004

[12] SSB, "Elektrisitet," 2019. [Online]. Available: https://www.ssb.no/energi-og-industri/statistikker/elektrisitet/maaned

[13] Nord Pool, "Historical Market Data." [Online]. Available: https://www.nordpoolgroup.com/historical-market-data/

[14] The Norwegian Tax Administration, "Tax on electric power," 2016. [Online]. Available: https://www.skatteetaten.no/globalassets/bedrift-og-organisasjon/avgifter/saravgifter/elektrisk-kraft/2016-elektrisk-kraft.pdf

[15] Fraunhofer ISE, "Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems," Study on behalf of Agora Energiewende, Tech. Rep., 2015.

[16] European Commission, "PVGIS." [Online]. Available: http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP

[17] J. Neubauer, K. Smith, E. Wood, and A. Pesaran, "Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries," Nathional Renewable Energy Laboratory, Tech. Rep. February, 2015.