SCCER CREST

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Innosuisse – Swiss Innovation Agency

WP3 - 2019/08

Balancing Market Design and Opportunity Cost – The Swiss Case

Moritz Schillinger

August 2019

Work Package 3: Energy Policy, Markets and Regulation
SCCER CREST

This research is part of the activities of SCCER CREST (Swiss Competence Center for Energy Research), which is financially supported by Innosuisse under Grant No. KTI. 1155000154.

Balancing Market Design and Opportunity Cost – The Swiss Case

Moritz Schillinger, University of Basel, +41 61 207 28 72, moritz.schillinger@unibas.ch

Abstract

In 2017, the Swiss electorate voted to transition the Swiss energy system towards energy efficiency and renewable energy resources. This transition entails many changes to the existing energy technologies and the supporting markets. In particular, this paper focuses on the Swiss electricity balancing markets and their adaptation in the context of the energy transition. I use an operational model for a set of Swiss hydropower plants to quantify the opportunity costs of balancing provision for hydropower under the past, current, and future Swiss balancing market designs. My results show that compared to the former balancing market design, significant cost savings can be achieved by the planned modifications. In addition, I show how the opportunity cost dynamics may change in the future with an increasing share of variable renewable energy in the system.

1 Introduction

Around the world, many countries are transforming their energy systems. Motivated to decrease CO_2 emissions, these countries are increasing the share of renewable energy (RE) technologies in their generation mix while decreasing the share of fossil-fuel based technologies. In addition, following the nuclear disaster at Fukushima Daiichi, countries like Germany or Switzerland are phasing out nuclear power as a part of their energy transitions.

With the energy transition, the system dynamics and requirements for security of supply change. With an increasing share of RE, energy production becomes less predictable, increasing the importance for ancillary services to secure a stable system operation. Of these services, balancing capacity and energy are becoming particularly important to ensure that electricity demand and supply are equal in real time (Ocker et al., 2018a).

Balancing capacity and energy are procured by the Transmission System Operators (TSOs) in so-called balancing markets. Today, balancing markets are mostly organized on a national level and vary widely in market design. In Europe, for example, no predominant balancing market design exists and market imperfections were observed in some countries in the past (Ocker et al., 2016). In order to reduce market imperfections and to adjust to the energy transition, governments and TSOs have been changing the designs of national balancing markets in recent years. In an effort to harmonize national balancing market designs across Europe, the European Commission (EC) published a guideline on electricity balancing market design. The EC created this guideline with the future goal of integrating national balancing markets to increase competition and efficiency. In the proposed changes in the guideline, the EC intended to facilitate the participation of new actors like variable renewable energies (VRE) or controllable loads (European Commission, 2017).

In line with the EC guideline, Switzerland adjusted its balancing market design in 2018 and plans to make further adjustments in the next few years. While the EC guideline is not legally binding for Switzerland since it is not a member of the European Union, it has to be implemented in the Swiss electricity system in case of a successful electricity agreement (Stromabkommen) between Switzerland and the EU (European Commission, 2017; Swissgrid, 2018a). With the adaptation, Switzerland addresses some of the key issues facing balancing market design: internalization, price mechanism, market incentives, and how to benefit from the synergies between products and the development of additional flexibility (Swissgrid, 2018a). In a previous paper (Schillinger and Weigt, 2019), we analyzed the past balancing market design[1] in Switzerland and showed that Swiss balancing market prices are defined by the opportunity cost of hydropower. In this paper, I dig deeper into how changes in the Swiss balancing market design influence the opportunity cost of hydropower for providing balancing services. In addition, I consider future changes in opportunity cost dynamics with an increasing share of VRE. To do so, I apply a hydropower operation model for a set of Swiss hydropower plants to derive their opportunity costs for balancing provision under the past, current, and

[1] In Schillinger and Weigt (2019), the Swiss balancing market design, which was in place before June 2018, was taken into account.

upcoming balancing market designs. Thereby, I use the Swiss market for secondary reserve (Sekundärregelleisung, SRL) as an example for balancing markets, only considering balancing capacity, not energy. To analyze the future changes in opportunity cost dynamics, I take into account future changes in the day-ahead market prices. My results show that by changing the product design from symmetric to asymmetric products as it was done in Switzerland in 2018, and from weekly to daily products as it is planned for 2019/2020, significant cost savings can be realized as compared to the past market design. The spring peak in balancing market prices, which is driven by hydrological conditions, can be significantly reduced by adjusting the Swiss balancing market design. My analysis of the future opportunity costs shows that the cost dynamics will change in the future due to an increasing share of VRE in the system.

The remainder of the paper is structured as follows: in section 2, I review the literature on balancing market design. In section 3, I show the changes in the Swiss balancing market design. In section 4, I explain the model and data used in this paper. In section 5, I illustrate the opportunity costs of hydropower for providing balancing capacity. I conclude in section 6.

2 Literature Review

In a well-functioning balancing market, balancing capacity prices are mainly defined by opportunity costs of the suppliers resulting from foregone spot market profits when bidding capacity into the balancing market (e.g., Aasgard and Roti, 2016; Heim and Götz, 2013; Just and Weber, 2008; Ocker et al., 2018b; Ocker, 2017). Since different technologies have different cost structures, the generation mix in a country is crucial for the costs of providing balancing services. Thus, balancing prices of a system with a high share of conventional (thermal) technologies might differ from balancing prices of a system dominated by hydropower or other RE (Müsgens et al., 2014; Ocker, 2017).

Beside the generation mix, the market design can have an impact on the balancing market prices. In this regard, many studies having a look at balancing auction design and its impact on the bidding strategy of the balancing suppliers (e.g., Ocker et al., 2018b; Ocker, 2017; Ocker and Ehrhart, 2017). Literature directly related to this study deals with specific market or product design elements and its impact on the market efficiency. In this paper I especially have a look at the timing and the (a-)symmetry of the balancing products since they are addressed by the adaptations in the Swiss balancing market design (see section 3). In this regard, Just (2011) explores the implication of different contract durations in the German balancing market. Using an equilibrium model for balancing markets and five different cases of contract durations, ranging from yearly to hourly periods, the author shows that with a shorter period the dispatch is more efficient and balancing capacity prices are lower. Besides the balancing capacity prices also the spot market prices are lower since less capacity is withheld from the spot market by the balancing market for shorter contract durations. The author highlights the importance of shorter contract durations to not deter smaller companies from participating in the market. Müsgens et al. (2012) also analyze the timing of German balancing markets. Besides having a look at the length of the binding period, the authors analyze how far before the beginning of the bidding period the auction should take place. Their results show that shortening the length of the time period for which balancing capacity has to be provided increases the efficiency of the market. Furthermore, holding auctions closer to the beginning of the bidding period can increase efficiency of the market due to lower uncertainty in the spot prices. Knaut et al. (2017) also have a look at the German balancing market by exploring the impact of the tender frequency on the market concentration. By using a numerical electricity market model the authors compare daily and hourly balancing products to weekly products while taking into account the possibility of pooling (i.e., individual power plants combined to a pool). Their results show a reduction in the procurement cost up to 15% by shorter periods. The effect of shorter tendering times on the market concentration is, however, not so clear since the authors also find cases in which shorter tendering times lead to higher market concentration.

Regarding the (a-)symmetry of balancing market products, Aasgard and Roti (2016) have a look at the Norwegian balancing market. Similar as in this paper (see section 4), the authors use a short-term hydropower operation model to determine the price for balancing capacity by the opportunity costs of a small hydropower system in the day-ahead market. By having a look at the different types of balancing products the authors show that spinning reserves, for which the plants have to run, have a significant impact on the day-ahead schedule and thus result in high opportunity costs. In addition, the authors show that symmetric balancing products, which require up and down regulation, are expensive since they further restrict the optimal day-ahead generation schedule.

Besides the difference in costs for symmetric and asymmetric balancing products, capacity costs differ for asymmetric positive and negative balancing products. As shown by Hirth and Ziegenhagen (2015), Müsgens et al. (2014) or Ocker et al. (2018b) the opportunity costs for providing positive and negative balancing capacity depend if a power plant is infra-marginal (i.e., in the money) or extra-marginal (i.e., out of the money). Plants which are infra-marginal have variable costs lower than the spot prices and are thus profitably producing in the spot market. For this plants, opportunity costs for negative balancing capacity are zero since they are running in the spot market anyway. If the plant provides positive balancing capacity, however, it cannot use its full capacity in the spot market. This causes losses in the spot market which are reflected in the opportunity cost for positive balancing capacity. If the plant is extra-marginal, its variable costs are higher than the spot market prices. Thus, the plant is not operating in the spot market and has to run just for the provision of negative balancing capacity. This is also the case for positive balancing capacity, at least for spinning reserves for which the plants have to run. The resulting losses in the spot market are priced into the balancing capacity bids.

Other market or product design aspects which are not directly considered in this paper (e.g., minimum bid size, Rammerstorfer and Wagner, 2009) can also have an impact on the market efficiency. In general, the balancing market or product design can be a barrier to entry for smaller companies (e.g., Just, 2011) or new sources of balancing reserves like VRE (e.g., Fernandes et al., 2016; Hirth and Ziegenhagen, 2015) and controllable loads or electric vehicles (e.g., Borne et al., 2018). To harmonize the highly heterogeneous balancing market design in Europe (see e.g., Entsoe, 2016; Ocker et al., 2016) and to enable the participation of new suppliers like VRE and controllable loads the EC published the Electricity Balancing

Guideline. According to the guideline, the procurement of positive and negative balancing capacity should be carried out separately and performed on short-term basis (European Commission, 2017). In regard to a balancing market harmonization as proposed by the EC, Dallinger et al. (2018) study the impact of a harmonized, common balancing capacity procurement among Austria, Germany, Belgium, and the Netherlands using an electricity and balancing market model. Their model results show that a harmonized and common procurement of balancing capacity can significantly reduce costs of balancing. Especially the asymmetric procurement of up- (i.e., positive) and downward (i.e., negative) balancing capacity as well as a shorter timing and product length, reduce costs of balancing and supports the integration of VRE and distributed energy resources (DERs) like controllable loads or electric vehicles.

With this paper, I contribute to literature in two main ways: first, I consider an energy system that is dominated by hydropower; and second, and perhaps most importantly, I look at the Swiss system, which is adopting its balancing market design in line with EU harmonization (see Swissgrid, 2018a). In a hydropower dominated system, opportunity costs and the resulting balancing market prices may differ from conventional (thermal) systems due to differences in technical characteristics (e.g., ramping time and part-load efficiency) and its dependence on natural circumstances (e.g., hydrology) (e.g., Müsgens et al., 2014; Ocker, 2017). Thus far, few studies have analyzed the Swiss balancing markets. However, the Swiss case offers an interesting test-case of the EU harmonization. Thus, by having a look at the changes in the Swiss balancing market design, I can also contribute insights on the future EU balancing market harmonization.

3 Swiss Balancing Market Design

In 2018, the Swiss balancing market design was modified. The modifications that were made, and those changes planned for the coming years, are driven by multiple factors: the transformation of the European energy systems; an increase in RE; national and European regulations such as the Swiss Energy Strategy 2050; the European Clean Energy Package legislation; the Electricity Balancing Guideline by the EC; and the increasing digitalization in the energy sector. The Swiss TSO Swissgrid plans to develop the Swiss balancing markets in four ways: internationalization of balancing markets, pricing mechanisms and market incentives, use of synergies between products and development of additional flexibility. All types of balancing reserves and energy, primary, secondary and tertiary, are addressed by the adaptation of the Swiss balancing market design. While the procurement and the call up of balancing energy will be increasingly coordinated by international cooperation, balancing capacity is mostly procured on national level (Swissgrid, 2018a). In this paper, I focus on the adaptations regarding balancing capacity, more precisely the changes in secondary reserves. Adaptations regarding other balancing reserves (e.g., primary and tertiary) and balancing energy are not considered in this paper.

In the SRL market, a first adaptation in market design was implemented in June 2018. Before June 2018, the Swiss TSO procured SRL one week before the actual delivery period and awarded capacity had to be reserved for the length of one week. Swissgrid tendered SRL capacity as a symmetric product, i.e., one product for up and downward regulation. The minimum bid size was 5MW and the maximum bid size per offer was 50MW—stepwise offers were possible. Approximately 400MW of SRL capacity were requested by the Swiss TSO. Swissgrid remunerated the awarded capacity by a pay-as-bid pricing mechanism while the market was cleared based on a cost minimization approach (Swissgrid, 2018a, 2017). With the adaptation of the SRL market design in June 2018 the Swiss TSO split positive and negative SRL into individual products (i.e., asymmetric products). Thus, suppliers can now bid separately for positive and negative SRL. In addition, the maximum bid size per offer was increased to 100 MW and stepwise offers over both products are possible (Swissgrid, 2018a, 2018b).

In 2019/2020 Swissgrid will adapt the Swiss SRL market design further. While the procurement of asymmetric products will continue, daily products can be traded in addition to weekly products. Thus, it will be possible to trade SRL the day before the actual delivery period. The length of time that the suppliers must reserve SRL capacity in the daily SRL tenders is not yet defined.

In 2022, Swissgrid envisages further changes in the Swiss SRL market design. While most of the market and product structure will be analogous to the design in 2019/2020, the Swiss SRL market will be adopted to be compatible with the "PICASSO" Project, an international platform for SRL procurement. In this context, the remuneration of awarded SRL capacity may change to a pay-as-cleared system instead of pay-as-bid (Swissgrid, 2018a).

In this paper, I focus on two main adaptations in the Swiss SRL market design, namely the change from symmetric to asymmetric products and the change from weekly to daily (here: 24-hour) products. Table 1 summarizes the main changes in the SRL market that I consider in this paper. Additional details on the SRL market, its adaptations, and the adaptations regarding the other balancing product types and markets can be found in Swissgrid (2018a).

Table 1: Adaptations in the market for secondary reserves in Switzerland which are considered in this paper (Swissgrid, 2018a).

	Past	Current	Future
Time frame	Until end of May 2018	From June 2018	From approx. 2019/ 2020
Timing	Previous week, for one week	Previous week, for one week	Previous week, for one week AND Day before, for unclear duration (here: 24 hours)
Supply structure	Symmetric (SRL+-)	Asymmetric (SRL+ and SRL-)	Asymmetric (SRL+ and SRL-)

4 Modelling framework

4.1 Model

To analyze the impact of the adaptations in the Swiss SRL market design on the opportunity cost for hydropower for providing SRL, I use a hydropower operation model. The basic model and opportunity cost logic that are applied in this paper are described in Schillinger and Weigt (2019). In the simple, linear and deterministic model adopted for this analysis, I do not consider trading options beyond the day-ahead market, uncertainty, or head effects. The plant operator's objective is to maximize his/her revenue in the day-ahead market taking generation and storage constraints into account. While in Schillinger and Weigt (2019) the model has a weekly time horizon, here I implement a yearly time horizon. The storage at the beginning and end of the year is given exogenously and water values (i.e., the future value of water) do not have to be taken into account explicitly. The model is defined such that it can be applied for single hydropower plants as well as cascades with multiple plants and reservoirs. This flexibility enables us to consider the diverse hydropower structures in Switzerland. I consider my market scenarios using this basic set up and a series of physical and contractual constraints associated with participation in the SRL market.

If the plant (or the cascade) is participating in the SRL market, it has to deviate from its optimal generation schedule on the day-ahead market. In a symmetric balancing market, the plant has to be able to decrease its capacity, which explains why the plant has to be operated at least at the capacity level that was bid into the SRL market. At the same time, the plant has to keep enough capacity free to be able to increase its capacity by the SRL quantity. In an asymmetric market, participating in the SRL market constrains the plant's capacity in only one direction at a time: either positive or negative. In addition to these capacity constraints, the plant needs to be able to deliver its SRL obligations in terms of energy if the TSO requires balancing energy to balance the system. Thus, if the plant participates in the SRL market it has to reserve enough water in the reservoir to be able to deliver balancing energy for the length of the bidding period (i.e., week or day). While in average only a small fraction of the actual balancing capacity is called up in case of a system imbalance (approx. 6%), I assume as in Schillinger and Weigt (2019) that the plant operator runs a zero risk strategy by ensuring that at all time enough water is reserved in the reservoir to be fully called up. To derive the opportunity cost for providing SRL in a specific week or day, I first run a model where the plant or cascade is optimized on the day-ahead market only. Second, I run a model in which capacity is bid into the balancing market for one week or day of the year and adopt the corresponding yearly generation schedule for the day-ahead market. By comparing the yearly revenue with and without balancing market participation in a specific week or day, I am able to calculate the opportunity costs of that week or day by the yearly revenue difference (Schillinger and Weigt, 2019). Additional details on the model as well as all model equations can be found in Schillinger and Weigt (2019).

4.2 Input data

To analyse the opportunity cost of hydropower for SRL under changing market designs, I chose a set of Swiss hydropower cascades. The eight selected cascades are representative of the whole inventory of Swiss storage hydropower plants, ranging from smaller plants with simple topologies to bigger cascades with complex structures. While I focus on storage hydropower in this paper, the cascades that are considered in my analysis may include run-of-river (RoR) plants in addition to storage plants; in practice, pure storage hydropower cascades are rare. The hydropower plants and data I use in this paper are the same as in Schillinger and Weigt (2019) and are based on Balmer (2006), Garrison et al. (2018), Schlecht and Weigt (2014) and SFOE (2018). The cascades differ, for example, in the number of plants and reservoirs per cascade, the cascade structure, or the turbine and storage capacity. In the results section, I focus on two of the cascades, a single-site (cascade No. 3 in Table A 1 in the appendix) that has a single plant and reservoir and a multi-site (cascade No. 7 in Table A 1 in the appendix) that has a bigger cascade containing multiple plants and reservoirs. Table 2 summarizes the main characteristics of the single- and multi-site. Data and results on the other cascades can be found in the appendix (A1).

Table 2: Data of selected hydropower cascades. Data based on Balmer (2006), Garrison et al. (2018), Schlecht and Weigt (2014), and SFOE (2018).

	Single-site	Multi-site
Turbine Capacity (MW)	60	397
Avg. Production (GWh/Year)	119	1036
Storage Capacity (Mio. m3)	40	204
Number of Plants	1	4
Number of Reservoirs	1	2
Reservoir full-load hours (Ratio Storage to Discharge*)	553	1643
Annual Inflow (Ratio Inflow to Storage*)	4	1

***** Based on largest reservoir of the cascade.

In addition to hydropower data, I need price data for my model. I use historical day-ahead market prices for Switzerland in 2015 from EPEXSPOT (2019). Besides the year 2015, the years 2013 and 2014 are analyzed for some of the cascades (see appendix A2). In addition to historical years, I take projected day-ahead market prices for the years 2030 and 2050 into account in order to derive potential changes in the SRL price dynamics in the future. Day-ahead market prices for 2030 and 2050 are simulated prices based on Schlecht and Weigt (2015). Figure 1 shows the day-ahead price dynamics for 2015, 2030, and 2050.

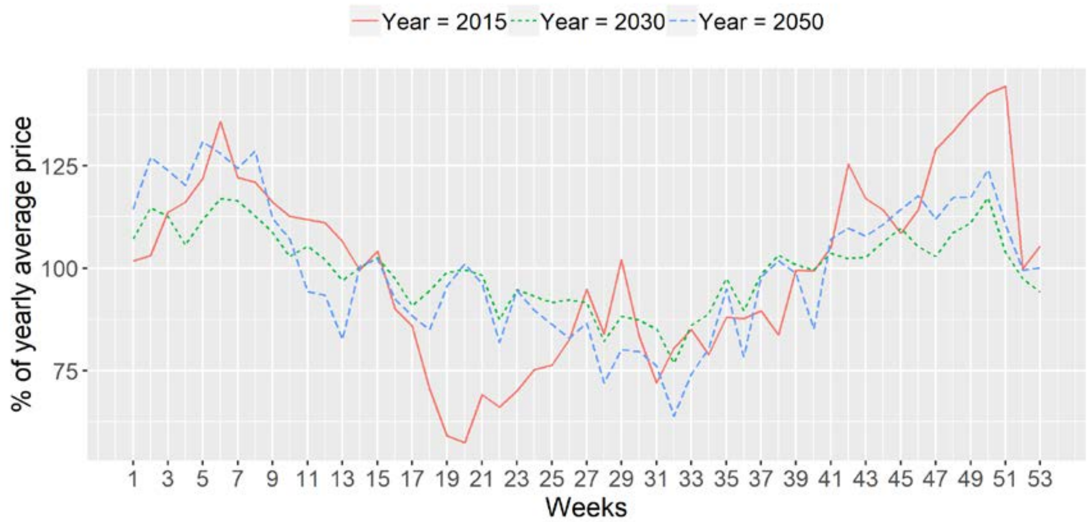


Figure 1: Day-ahead price by week relative to yearly average day-ahead price. Prices for 2015 are from EPEXSPOT (2019), prices for 2030 and 2050 are based on Schlecht and Weigt (2015).

As illustrated in Figure 1, models of the day-ahead price dynamics in 2030 and 2050 show changes driven by a significant increase in VRE and a decrease in fossil-fuel based technologies in Europe. While the Swiss prices in 2015 are especially affected by hydrological conditions (i.e., minimum in May when the inflows are high), models predict that the future price dynamics will be more influenced by the infeed of wind and solar in Europe. In particular, the increase in solar power penetration will decrease prices in summer (i.e., minimum prices in 2030 and 2050 in August when solar infeed is high).

5 Results

In this section, I first show the impact of a change from symmetric to asymmetric products on the opportunity cost of hydropower for providing SRL. Afterwards, I analyse the introduction of daily SRL products. These results are illustrated under historical conditions taking the year 2015 as example. After historical analysis, I look at the future changes in the opportunity cost dynamics under the future SRL market design (i.e., asymmetric weekly and daily SRL products). I focus on the results for a SRL bid size of 30MW except in the illustration of the yearly costs. Results on additional historical years (2013 and 2014 for cascade No. 3 and 7), additional cascades, and SRL bid sizes can be found in the appendix (A2).

5.1 Historical

5.1.1 Symmetric vs. asymmetric products

In June 2018, asymmetric weekly SRL products were introduced in the Swiss SRL market. In contrast to before this design change, firms or plants can now bid separately for positive or negative SRL. This shift from symmetric to asymmetric products has an impact on the cost of hydropower for providing these products. Figure 2 compares the yearly opportunity cost for separate bids for positive (pos) and negative (neg) SRL with the cost for symmetric SRL bids. Relative costs are illustrated for different SRL bid sizes and sites for the year 2015. While in case of the single-site, a single hydropower plant is bid into the balancing market, a portfolio of multiple hydropower plants is bid into the market in case of the multi-site.

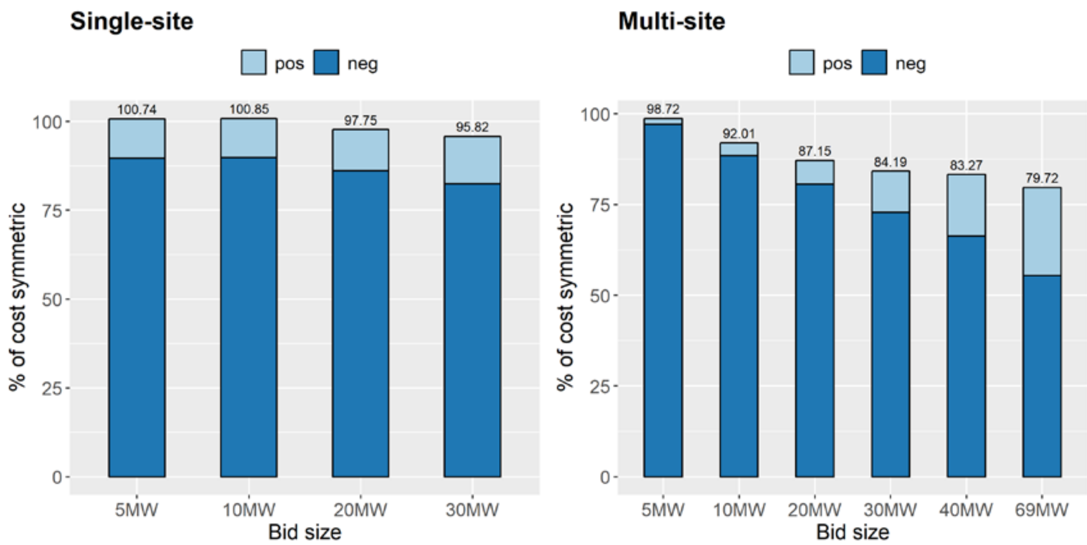


Figure 2: Cost per year for asymmetric weekly SRL relative to symmetric weekly SRL by bid size and cascade.

As shown in Figure 2, bidding separately for positive and negative SRL can reduce costs to provide these products compared to a symmetric SRL provision. While at lower SRL bid sizes, cost for symmetric or asymmetric SRL provision are similar, cost reduction can be realized at higher SRL bid sizes. At low SRL bid sizes, SRL provision has only a limited impact on the day-ahead generation schedule. However, at higher bid sizes significant changes in the day-ahead generation schedule occur when providing SRL. Thus, cost reductions, which can be achieved by the introduction of asymmetric SRL products, increase (non-proportional) with the increase in the SRL bid size.

Comparing positive and negative SRL, the provision of negative SRL comes at a high cost for storage hydropower plants. While a storage hydropower plant would only produce in a few high price hours if just active on the day-ahead market, it has to run baseload at the offered capacity level for the whole week if participating in the negative SRL market. Such a change in the day-ahead market schedule would limit its possibility to benefit from high price hours of the year since the water availability in the reservoir is reduced. For the provision of positive SRL, the amount of capacity that can be bid into the day-ahead market is limited. Thus, the provision of positive SRL has a smaller impact on the day-ahead generation schedule which is why it can be provided at lower cost (see also generation and storage in the appendix A2.1 and A2.2).

Comparing single- to multi-sites, at higher SRL bid sizes the cost for providing positive SRL increase in the total cost share for multi-sites. At higher bid sizes, the provision of positive SRL becomes more constraining for the day-ahead generation schedule. At the same time, cost reductions in negative SRL are increasing for multi-sites with higher SRL bid sizes. While the provision of negative SRL can be costly for storage hydropower plants, it can be provided at lower cost for RoR plants, which are running baseload anyway. Since cascades can be bid as a portfolio of plants into the SRL market and include RoR plants in addition to storage plants, multi-sites can provide negative SRL at a lower cost. In addition, multi-sites have a higher flexibility in general since they are able to coordinate their SRL obligations among the plants and reservoirs of the cascade (see also Schillinger and Weigt, 2019). By introducing asymmetric SRL products, multi-sites can achieve a higher cost reduction compared to single-sites. While in Figure 2 it looks like especially multi-sites are benefiting from the introduction of asymmetric products since they have higher costs savings as the single-sites, it is also beneficial for the single-sites. In this paper, I force the plants and cascades to provide positive and negative balancing capacity at all times. In reality, with the introduction of asymmetric products, however, single-sites are not forced anymore to provide costly negative SRL as with symmetric products. Each site can now choose which product to provide at which time. Thus, each site can do what it can do best. At which time of the year the provision of 30MW of SRL is costly for the individual sites is illustrated in Figure 3.

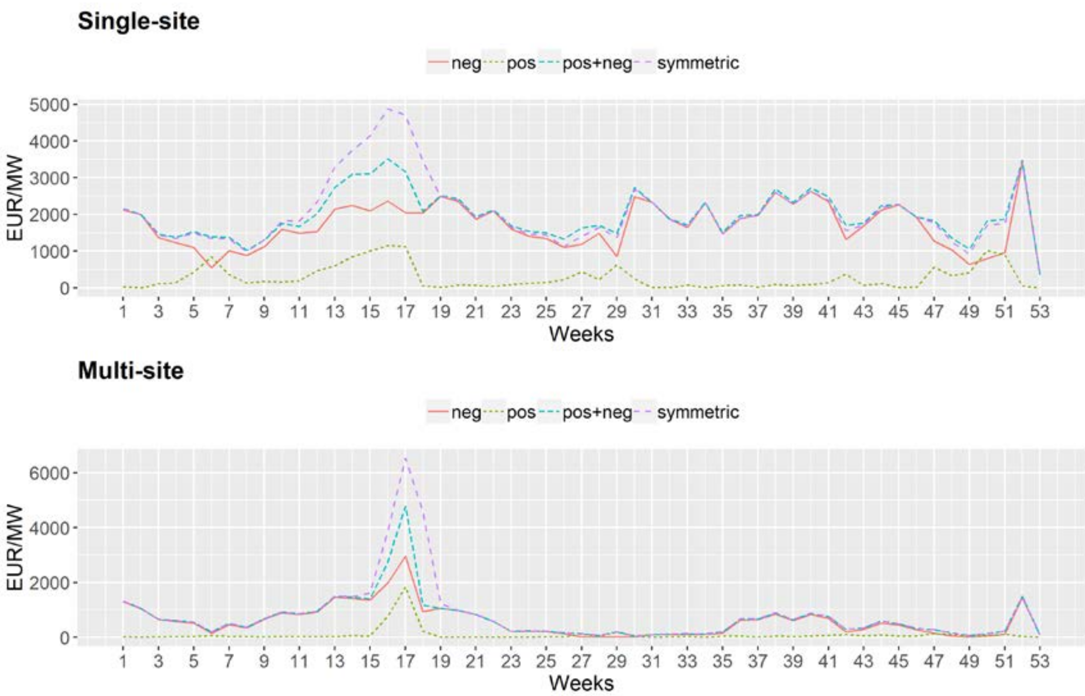


Figure 3: Opportunity cost for 30 MW of weekly symmetric and asymmetric SRL by cascade.

Naturally, hydropower is influenced by hydrological conditions throughout the year. Thus, the opportunity cost for providing SRL, and consequently, the SRL prices are driven by hydrological conditions throughout the year. As illustrated in Figure 3, the opportunity cost for SRL peak in spring (weeks 13-21). Since the storage reservoirs are empty at that time and the snow melt has not begun yet, water availability and, consequently, the flexibility of hydropower plants are low (see also storage in the appendix A2.2). Therefore, providing SRL at that time is costly. Since the low runoff in spring does not just influence storage power plants but also RoR plants, bigger cascades have high opportunity cost during spring as well (see also Schillinger and Weigt, 2019).

With the introduction of asymmetric SRL products, the spring peak still persists but at a lower level. Since the opportunity cost for positive and negative SRL are in sum (pos+neg) similar to the opportunity cost for symmetric SRL in all other weeks of the year, the reductions in the yearly cost, as illustrated in Figure 2, can be attributed to a reduction in the opportunity cost in spring. This is also true for other SRL bid sizes (see appendix A2.3). Having a look at the individual products, we can see that both the cost for negative SRL and the cost for positive SRL are relatively high in the spring. However, as discussed before, providing negative SRL is more costly for storage hydropower plants than the provision of positive SRL. As illustrated for the single-site, especially for pure storage power plants, the provision of negative SRL is cheaper in times when the day-ahead market prices are high. If prices are high, the plant is producing in the day-ahead market and does not have to be started up just for the provision of negative SRL. At the same time, positive SRL is more costly if the prices are high, since the storage power plant cannot use its full capacity in the day-ahead market (see, e.g., week 6 and 50 and prices in chapter 4). With the introduction of asymmetric products the plants can now choose at which time to provide which product in order to maximize its profits. Thus, the single-site would provide negative SRL especially in times it is producing anyway while providing positive SRL in times it is not running at full-load in the spot market. For the multi-site, the price impact is less obvious, since the cascade includes also RoR plants for which the generation is defined by inflows but not prices.

5.1.2 Daily products

In 2019/ 2020, Swissgrid will introduce daily asymmetric SRL products. While the actual contract length (i.e., for how long capacity has to be reserved) is not yet defined, I assume a contract length of one day (i.e., 24 hours) in this analysis. However, Swissgrid may set the contract length to a shorter period, such as in the TRL market where 4-hour blocks are traded (Swissgrid, 2018a). In Figure 4 I depict the yearly opportunity cost change between daily asymmetric products and symmetric weekly products.

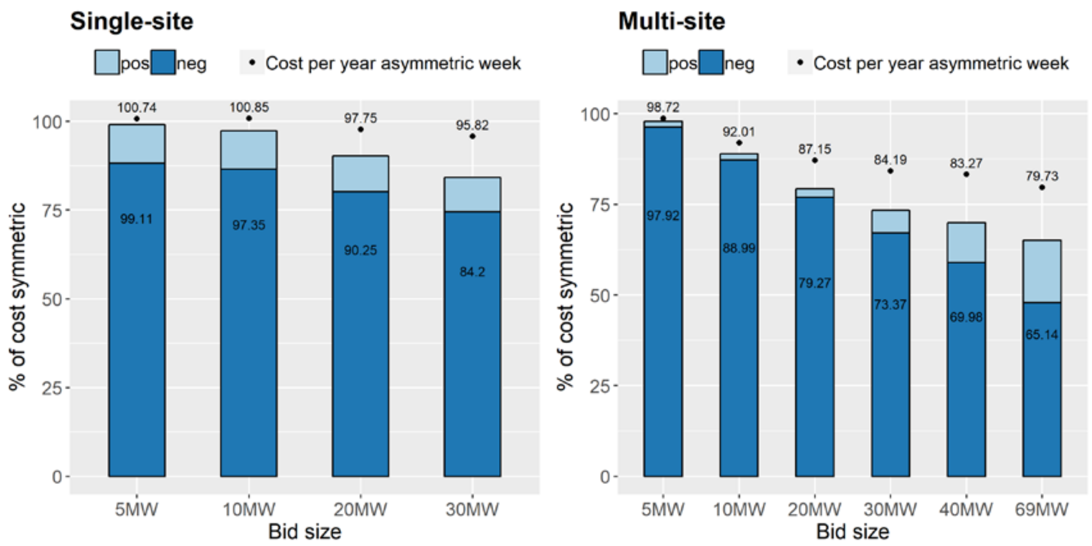


Figure 4: Cost per year for asymmetric daily SRL relative to symmetric weekly SRL by bid size and cascade.

My analysis shows that introducing daily SRL products can further reduce the opportunity costs for hydropower producers. The effect is greater for higher SRL bid sizes. For example, at a bid size of 30MW, costs are approximately 15% (single-site) and 25% (multi-site) lower as compared to the cost of symmetric SRL products. Compared to weekly asymmetric SRL products, daily asymmetric products reduce the costs by approximately 10%. SRL provision becomes less restrictive for hydropower when the contract length is shortened. Compared to weekly SRL products, daily SRL products allow hydropower producers to retain more flexibility and deviate less from the optimal generation schedule (see also generation and storage in the appendix A2.1 and A2.2).

In Figure 5, I show the weekly opportunity cost for the single-site for a bid size of 30MW by SRL product design. The opportunity cost for daily SRL products are illustrated as weekly sum. The weekly sum of the daily opportunity costs should be interpreted as a lower bound since the opportunity costs for daily SRL are calculated independently for each day of a week. However, if the plant would bid multiple days of a week in the daily SRL market the weekly opportunity costs would be higher since capacity and water would have to be reserved not just for a single day but for multiple days.

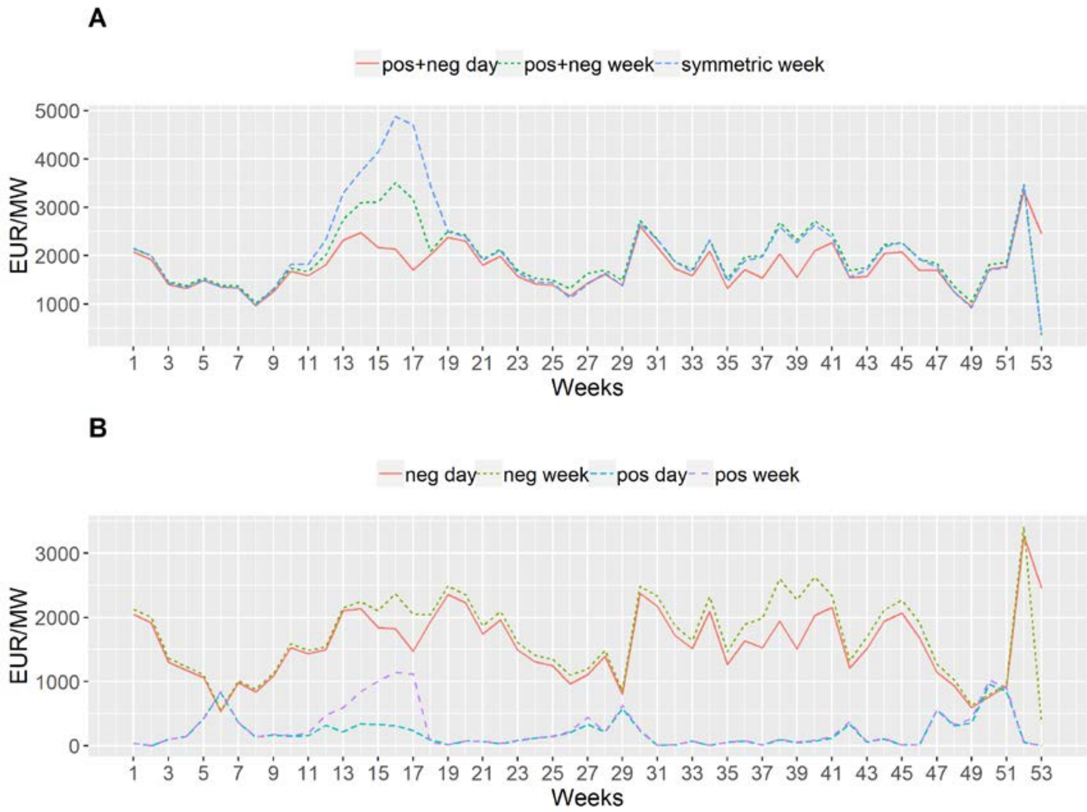


Figure 5: Opportunity costs for 30 MW of symmetric and asymmetric SRL by duration for single-site plant. (A) shows the sum over positive and negative products, (B) is split up by direction. Opportunity costs for daily SRL are illustrated as weekly sum.

As shown in Figure 5A, daily SRL products mitigates the spring peak in the total opportunity costs (i.e., the sum of costs for positive and negative SRL) for the single-site. Since water has to be reserved just for a day instead of a week, costs for providing SRL at that time are much lower. In addition to the cost reductions in spring, the opportunity costs in other weeks of the year can be reduced as well. Especially in early fall, further cost reductions by daily asymmetric SRL products can be realized. As I show in Figure 5B, the spring peak disappears because the opportunity costs for both, positive and negative, SRL products are lower. However, in the fall, we see opportunity costs decrease due to less costly negative SRL. If the plant would be active just on the day-ahead market at that time, its generation would be rather low due to unfavorable market prices. If the plant bids into the weekly symmetric or asymmetric SRL market, its generation has to be significantly increased during that time in order to provide negative SRL. If the plant bids for daily SRL, it must also increase its generation, but since the capacity and the water has to be reserved just on a daily basis, the plant is able to operate closer to the optimal day-ahead generation schedule (see also generation in the appendix A2.1). Thus, providing SRL in early fall comes at a lower cost if provided on daily instead of a weekly basis.

The results for a multi-site show similar patterns. In Figure 6 I show the weekly opportunity cost for the multi-site for a bid size of 30MW by SRL product design.

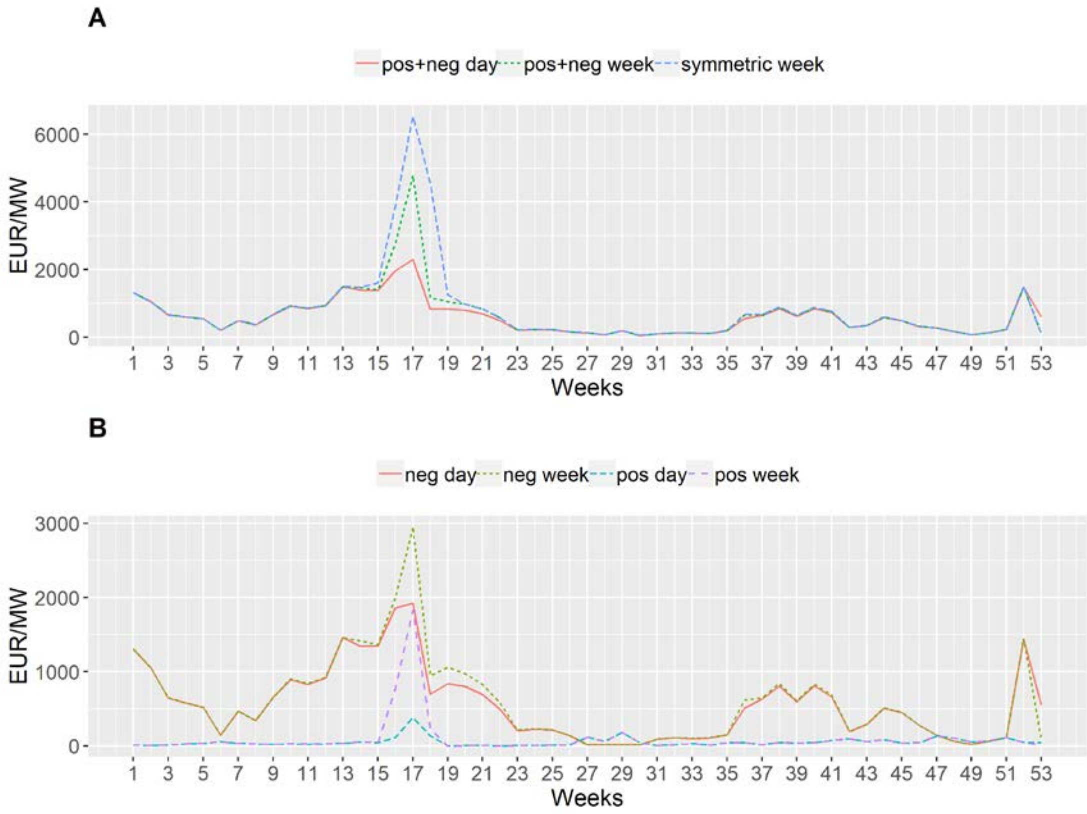


Figure 6: Opportunity costs for 30 MW of symmetric and asymmetric SRL by duration for multi-site plant. (A) shows the sum over positive and negative products, (B) is split up by direction. Opportunity cost for daily SRL are illustrated as weekly sum.

As for the single-site, daily asymmetric SRL products reduce the spring peak in the opportunity costs for the multi-site (see Figure 6A). However, for the multi-site the highest opportunity cost of the year still occur in spring but on a much lower level as compared to weekly products. Unlike the single-sites, multi-sites do not enjoy opportunity cost reductions during other weeks of the year. As illustrated in Figure 6B, the cost reductions in spring results from lower costs in both positive and negative daily SRL. In particular, daily SRL products significantly reduces the cost for positive SRL.

5.2 Future

The increase in VRE in Europe in the future will change the day-ahead market price dynamics (see prices in chapter 4). If the day-ahead market price dynamics change, the opportunity cost and SRL price dynamics will change also. I illustrate these changes to the opportunity cost dynamics in 2030 and 2050 compared to 2015 under the future SRL market design (i.e., weekly and daily asymmetric SRL products). Thus, I assume that there will be no further changes in the Swiss SRL market design beside the ones considered in this paper. In Figure 7, opportunity costs for the single-site are illustrated as the sum over positive and negative. In Figure 7A, I show the cost dynamics for weekly products, and in Figure 7B, I show the cost dynamics for daily products.

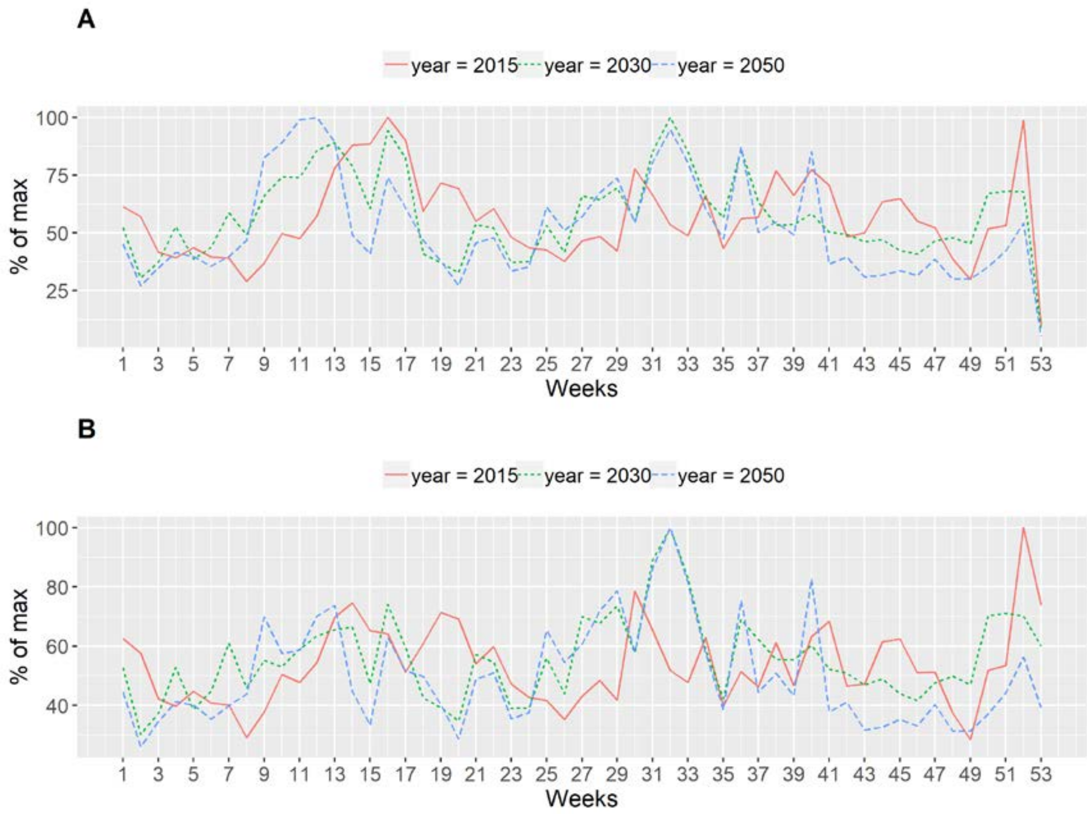


Figure 7: Changes in opportunity cost dynamics by 2030 and 2050 for 30MW of (A) weekly and (B) daily asymmetric SRL for single-site plant. Opportunity costs are the sum over positive and negative opportunity costs. Changes for daily SRL are illustrated as weekly sum.

In the future analysis, I assume that inflow values for 2030 and 2050 are equal to the inflows in 2015. Thus, hydrological conditions are the same in 2030 and 2050; therefore, I can isolate the impact of changes in the day-ahead market dynamics on the opportunity costs dynamics. In 2015, Swiss day-ahead market prices are defined by the electricity demand and the hydrology. In winter, when the demand is high but the runoff is low and thus hydropower availability reduced, prices are high. With the snow melt in spring, runoff and hydropower availability are high and prices are low (e.g., minimum day-ahead prices in 2015 in May). In 2030 and 2050, the low-price period shifts to summer when the in-feed of solar is high in Europe (e.g., minimum prices in 2030 and 2050 in August). The high price hours, however, still occur in winter due to a high demand, a low hydropower availability and lower in-feed from solar (see prices Figure 1).

The changes in the day-ahead price dynamics in the future also influence the day-ahead generation schedules of the hydropower plants (see generation appendix A2.1). Depending on the day-ahead price level and if storage hydropower plants would produce at that price level, providing SRL can be more or less costly. Lower day-ahead market prices in the summers reduces the incentive for storage hydropower plants to produce. If generation is low, the opportunity costs for providing SRL (i.e., negative SRL) are high since major adaptation in the day-ahead generation schedule are necessary to provide SRL. As I illustrate in Figure 7, providing SRL in summer comes at a higher cost in the future. In many weeks in the springs of 2030 and 2050 prices are higher as in 2015. Storage plants generate more during this time to benefit from those prices. With a higher generation, storage plants can participate in SRL—especially negative SRL—at lower cost because the plant is running in more hours and would not have to start up for SRL provision. At the beginning of spring, prices in 2030 and 2050 are less favorable for storage hydropower plants than in 2015. Consequently, generation is lower at that time and opportunity costs are higher (see also generation in the appendix A2.1).

I find little difference between the opportunity costs dynamics when comparing 2030 to 2050. However, due to an increased share of VRE in 2050 relative to 2030, day-ahead prices in 2050 are higher in winter and lower in summer (relative to the yearly average, Figure 1). The differences in prices in 2030 and 2050 also cause the day-ahead generation schedules and the opportunity costs for SRL to diverge. The opportunity costs for daily and weekly SRL products are similar in 2030 and 2050 (see Figure 7A and 7B). However, while the changes in the opportunity costs for daily and weekly products are similar in summer, opportunity costs for daily SRL are generally lower in spring.

In Figure 8, I show the results for the same future analysis in the multi-site case.

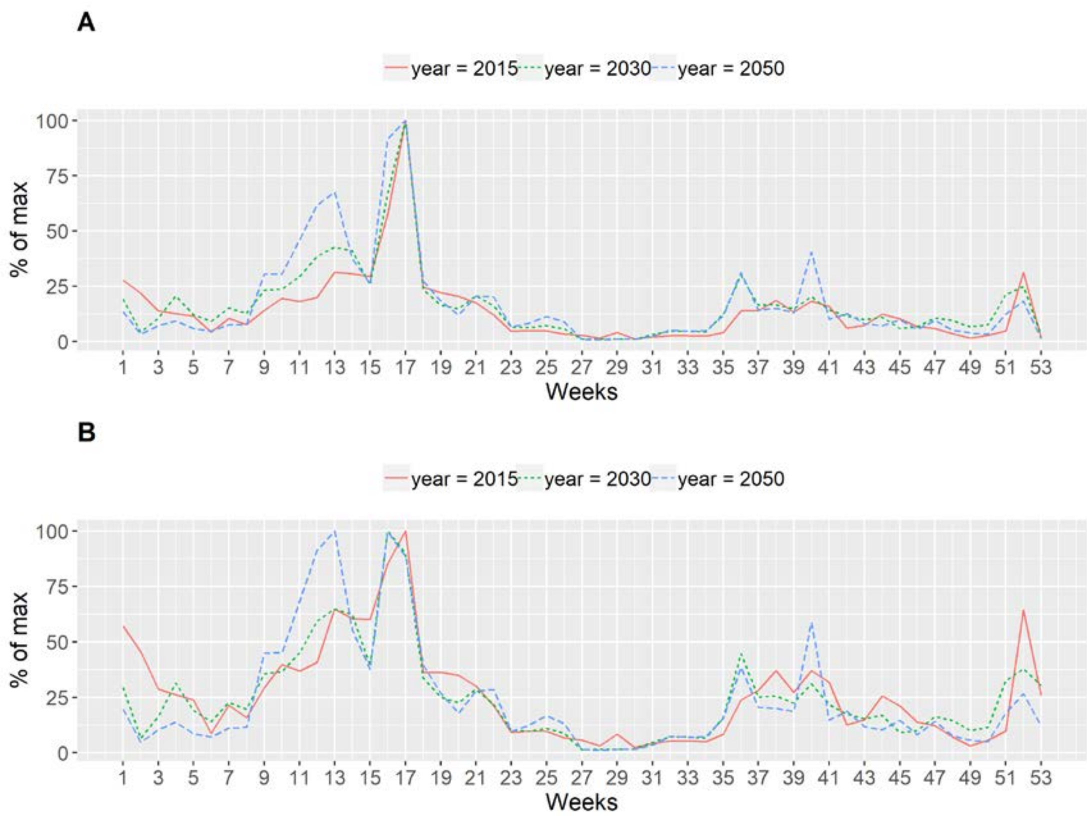


Figure 8: Changes in opportunity cost dynamics by 2030 and 2050 for 30MW of (A) weekly and (B) daily asymmetric SRL for multi-site plant. Opportunity costs are the sum over positive and negative opportunity costs. Changes for daily SRL are illustrated as weekly sum.

We can see that the multi-site's opportunity costs for weekly (Figure 8A) and daily (Figure 8B) asymmetric SRL products in 2030 and 2050 increase much less in summer than for a single-site. Multi-sites are less dependent on prices because of RoR generation in the cascade. However, in late summer and the beginning of fall, we observe increases in the opportunity costs due to lower day-ahead prices and lower day-ahead generation compared to 2015 (see also generation in the appendix A2.1). Opportunity costs also significantly increase at the beginning of spring. At that time, generation of the cascade is more price dependent since inflows and RoR generation are low. Thus, as for the single-site, changes in the day-ahead price dynamics in 2030 and 2050 lead to significant increases in the opportunity costs during spring for the multi-site. Overall, the opportunity cost dynamics of the multi-site show fewer changes in the future relative to the single-site because RoR generation of the multi-site is dependent on inflows and not on market prices.

6 Discussion

In this paper, I consider the current and proposed changes to the Swiss SRL balancing market.[2] My results show that a change from symmetric to asymmetric, and from weekly to daily balancing products can significantly reduce the cost of balancing capacity. In 2015, total capacity cost for SRL in Switzerland was approx. 78 Mio. EUR (Abrell, 2016). Putting these costs into the context of my historical results is difficult since I do not have any information which plants, cascades or portfolios of different technologies are active in the market in reality. However, assuming that only single-site plants identical to the one considered in this paper would satisfy the demand for balancing capacity, up to 3 Mio. EUR could be saved by introducing weekly asymmetric products and up to 12 Mio. EUR by introducing daily asymmetric products. If multi-sites, identical to the one in this paper, completely satisfied the market, introducing weekly (daily) asymmetric SRL products could lead to cost savings up to 16 Mio. EUR (27 Mio. EUR). However, since the SRL market is satisfied by multiple cascades, which include a mix of single- and multi-sites with unique characteristics, the costs savings which can be realized by changing the Swiss balancing market design may vary from these numbers in reality.

My findings on the impact of the adaptations in the balancing market design are in line with previous studies. For example, Aasgard and Roti (2016) also find lower costs for asymmetric than for symmetric balancing products. The cost for asymmetric positive and negative balancing capacity depends if a plant is infra- or extra-marginal (e.g., Hirth and Ziegenhagen, 2015; Müsgens et al., 2014; Ocker et al., 2018b). My results also agree with Müsgens et al. (2012), Just (2011) or Knaut et al. (2017) who find that shortening the length of the time period for which balancing capacity has to be provided can significantly decrease costs. Reducing the

[2] In Switzerland, SRL represents the biggest cost share of the total balancing costs (Abrell, 2016); therefore, I did not consider other balancing markets (i.e., primary and tertiary).

contract duration not just to a day but even further (e.g., to an hourly basis) could further reduce the costs for providing balancing capacity (Just, 2011).

As my results show, the propositions by the EC (European Commission, 2017) which are considered in this paper are promising for increasing efficiency in balancing markets, at least for a hydropower dominated electricity system like Switzerland. Furthermore, the adaptations in the balancing markets in Switzerland and other countries reduce the barriers for the participation of other actors like, for example, VRE and controllable loads because the new market design better suits the technical characteristics of these actors. And, if additional actors participate in the SRL market, additional efficiency gains may be possible (Borne et al., 2018; Fernandes et al., 2016). For example, if more actors participate in the SRL market, the prices may no longer be purely defined by the opportunity costs of hydropower.

The adaptations in the balancing market design proposed by the EC also encourage the countries to integrate balancing markets across borders (European Commission, 2017). By adapting the Swiss balancing market design to the European one, Switzerland increases the possibilities to fully integrate into a European market. In an integrated balancing market, even further cost savings are possible (Dallinger et al., 2018). Though not considered in this study, other Swiss balancing markets (i.e., primary and tertiary) will adapt their design in the near future and the activation of balancing energy will be increasingly internationally coordinated (Swissgrid, 2018a). The effect of these developments in primary and tertiary balancing markets and international integration are important topics for future studies.

The analysis carried out in this paper is subject to several limitations. One limitation is that I use a simplified linear and deterministic hydropower operation model to derive the opportunity costs under various market designs. Taking into account uncertainty as well as non-linear hydropower plant characteristics may change the opportunity costs of hydropower for providing balancing capacity (see also Schillinger and Weigt, 2019). In addition, I only take a limited set of Swiss hydropower plants into account. Though I chose my set to be representative of the Swiss hydropower fleet, in reality each hydropower plant and cascade is unique in its characteristics. As a result, demonstrated cost changes may be quantitatively different in reality. In addition, bigger cascades than the ones considered in this paper or even a portfolio of different technologies can be active in balancing markets in reality. This could lead to lower opportunity costs for balancing services than illustrated in this paper. Finally, more detailed data on Swiss hydropower could lead to more precise results. In this paper for example, I use inflow data with a monthly time resolution. However, inflow dynamics within months have an impact on the generation schedules of hydropower plants as well.

7 Conclusion

In this paper, I analysed the impact of the adaptations in the Swiss balancing market design on the opportunity cost of hydropower for providing balancing services. To do this I used a hydropower operation model and a set of Swiss hydropower plants and cascades. My results show that a change from symmetric to asymmetric, and from weekly to daily balancing products can significantly reduce the cost of balancing capacity. The change in market design particularly reduces the spring peak in balancing prices. In addition, I show that the opportunity cost dynamics may change in the future with an increasing share of VRE. Though my results are subject to some limitations, the current and future changes in the Swiss balancing market design seem to be promising in terms of potential efficiency gains. Furthermore, the adaptations in the balancing market design can support the integration of renewable energies and the implementation of the Swiss energy strategy 2050.

References

Aasgard, E.K., Roti, P.H., 2016. Opportunity-cost-pricing of reserves for a simple hydropower system, 1–5. 10.1109/EEM.2016.7521331.

Abrell, J., 2016. The Swiss Wholesale Electricity Market. SCCER CREST Working Paper (WP3-2016/07).

Balmer, M., 2006. Schweizer Wasserkraftwerke im Wettbewerb: Eine Analyse im Rahmen des europäischen Elektrizitätsversorgungssystems. vdf Hochsch.-Verl. an der ETH, Zürich, 208 pp.

Borne, O., Korte, K., Perez, Y., Petit, M., Purkus, A., 2018. Barriers to entry in frequency-regulation services markets: Review of the status quo and options for improvements. Renewable and Sustainable Energy Reviews 81, 605–614. 10.1016/j.rser.2017.08.052.

Dallinger, B., Auer, H., Lettner, G., 2018. Impact of harmonised common balancing capacity procurement in selected Central European electricity balancing markets. Applied Energy 222, 351–368. 10.1016/j.apenergy.2018.03.120.

Entsoe, 2016. Survey on Ancillary Services Procurement and Electricity Balancing Market Design. https://docstore.entsoe.eu/publications/market-reports/ancillary-services-survey/Pages/default.aspx. Accessed 11 February 2019.

EPEXSPOT, 2019. Marktdaten. https://www.epexspot.com/de/marktdaten. Accessed 7 February 2019.

European Commission, 2017. Electricity Balancing Guideline: Commission Regulation (EU) 2017/2195 of 23 November 2017 Establishing a Guideline on Electricity Balancing. https://eur-lex.europa.eu/legalcontent/EN/TXT/?uri=uriserv:OJ.L_.2017.312.01.0006.01.ENG&toc=OJ:L:2017:312:TOC. Accessed 7 February 2019.

Fernandes, C., Frías, P., Reneses, J., 2016. Participation of intermittent renewable generators in balancing mechanisms: A closer look into the Spanish market design. Renewable Energy 89, 305–316. 10.1016/j.renene.2015.12.037.

Garrison, J.B., Demiray, T., Abrell, J., Savelsberg, J., Weigt, H., Schaffner, C., 2018. Combining Investment, Dispatch, and Security Models - An Assessment of Future Electricity Market Options for Switzerland, 1–6. 10.1109/EEM.2018.8469895.

Heim, S., Götz, G., 2013. Do pay-as-bid auctions favor collusion? - Evidence from Germany's market for reserve power. Joint Discussion Paper Series in Economics by the Universities of Aachen Gießen Göttingen Kassel Marburg Siegen (No. 24-2013).

Hirth, L., Ziegenhagen, I., 2015. Balancing power and variable renewables: Three links. Renewable and Sustainable Energy Reviews 50, 1035–1051. 10.1016/j.rser.2015.04.180.

Just, S., 2011. Appropriate contract durations in the German markets for on-line reserve capacity. J Regul Econ 39 (2), 194–220. 10.1007/s11149-010-9141-0.

Just, S., Weber, C., 2008. Pricing of reserves: Valuing system reserve capacity against spot prices in electricity markets. Energy Economics 30 (6), 3198–3221. 10.1016/j.eneco.2008.05.004.

Knaut, A., Obermüller, F., Weiser, F., 2017. Tender Frequency and Market Concentration in Balancing Power Markets. EWI Working Paper (No 17/04).

Müsgens, F., Ockenfels, A., Peek, M., 2012. Balancing Power Markets in Germany: Timing Matters. Z Energiewirtsch 36 (1), 1–7. 10.1007/s12398-011-0068-7.

Müsgens, F., Ockenfels, A., Peek, M., 2014. Economics and design of balancing power markets in Germany. International Journal of Electrical Power & Energy Systems 55, 392–401. 10.1016/j.ijepes.2013.09.020.

Ocker, F., 2017. Design and performance of European balancing power auctions, 1–6. 10.1109/EEM.2017.7981861.

Ocker, F., Braun, S., Will, C., 2016. Design of European balancing power markets, 1–6. 10.1109/EEM.2016.7521193.

Ocker, F., Ehrhart, K.-M., 2017. The "German Paradox" in the balancing power markets. Renewable and Sustainable Energy Reviews 67, 892–898. 10.1016/j.rser.2016.09.040.

Ocker, F., Ehrhart, K.-M., Belica, M., 2018a. Harmonization of the European balancing power auction: A game-theoretical and empirical investigation. Energy Economics 73, 194–211. 10.1016/j.eneco.2018.05.003.

Ocker, F., Ehrhart, K.-M., Ott, M., 2018b. Bidding strategies in Austrian and German balancing power auctions. WIREs Energy Environ 7 (6), e303. 10.1002/wene.303.

Rammerstorfer, M., Wagner, C., 2009. Reforming minute reserve policy in Germany: A step towards efficient markets? Energy Policy 37 (9), 3513–3519. 10.1016/j.enpol.2009.03.056.

Schillinger, M., Weigt, H., 2019. Bidding into balancing markets in a hydro-dominated electricity system. FoNEW Discussion Paper (2019/1).

Schlecht, I., Weigt, H., 2014. Swissmod: A Model of the Swiss Electricity Market. FoNEW Discussion Paper (2014/1).

Schlecht, I., Weigt, H., 2015. Linking Europe: The Role of the Swiss Electricity Transmission Grid until 2050. Swiss J Economics Statistics 151 (2), 125–165. 10.1007/BF03399415.

SFOE, 2018. Statistik der Wasserkraftanlagen der Schweiz. http://www.bfe.admin.ch/themen/00490/00491/index.html?lang=de&dossier_id=01049 . Accessed 7 February 2019.

Swissgrid, 2017. Grundlagen Systemleistungsprodukte: Produktbeschreibung - gültig ab Februar 2017. https://www.swissgrid.ch/de/home/customers/topics/ancillary-services/as-documents.html. Accessed 14 February 2019.

Swissgrid, 2018a. Balancing Roadmap Schweiz. https://www.swissgrid.ch/de/home/operation/regulation/ancillary-services.html. Accessed 7 February 2019.

Swissgrid, 2018b. Grundlagen Systemleistungsprodukte: Produktbeschreibung - gültig ab Juni 2018. https://www.swissgrid.ch/de/home/customers/topics/ancillary-services/as-documents.html. Accessed 14 February 2019.

Appendix

A1 Data

Table A 1: Data of selected hydropower cascades. Based on Balmer (2006), Garrison et al. (2018), Schlecht and Weigt (2014) and SFOE (2018).

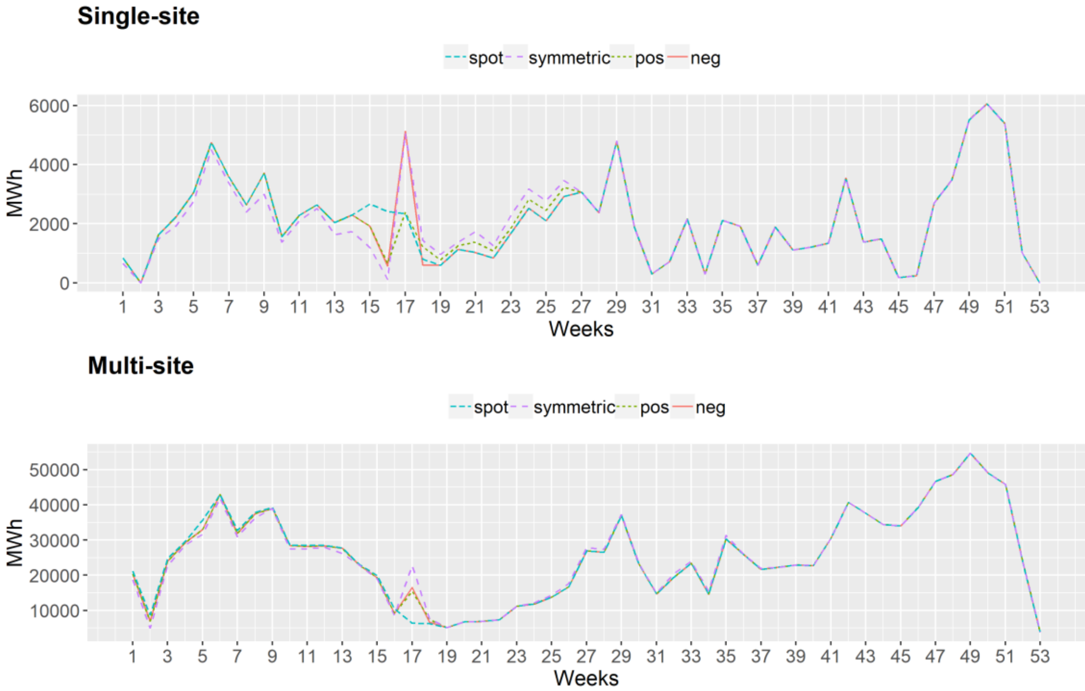
Cascade No.	Capacity (MW)	Avg. Production (GWh)	Storage (Mio. m3)	Number Plants/ Reservoirs	Ratio Storage to Discharge*	Ratio Inflow to Storage*
1	54	72	50	1/1	434	3
2	56	214	20	2/2	556	7
3	60	119	40	1/1	553	4
4	104	318	6	3/2	199	17
5	109	227	86	2/1	462	5
6	201	702	62	5/3	998	3
7	397	1’036	204	4/2	1’643	1
8	439	925	111	3/3	1’489	2

* Based on largest reservoir of the cascade.

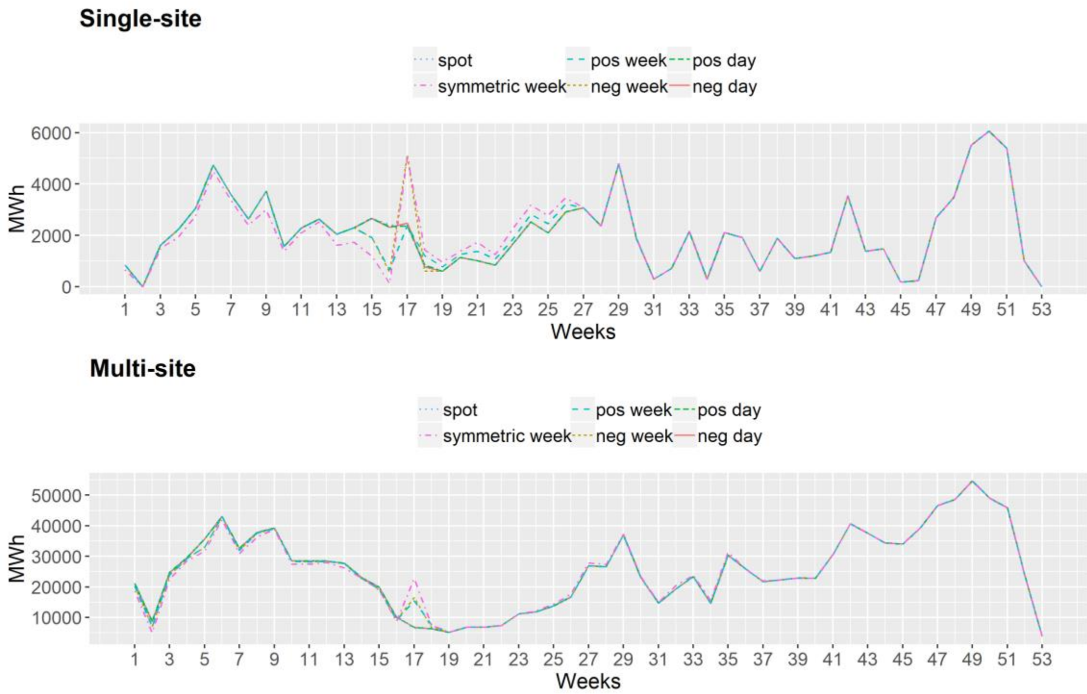
A2 Additional Results

A2.1 Generation

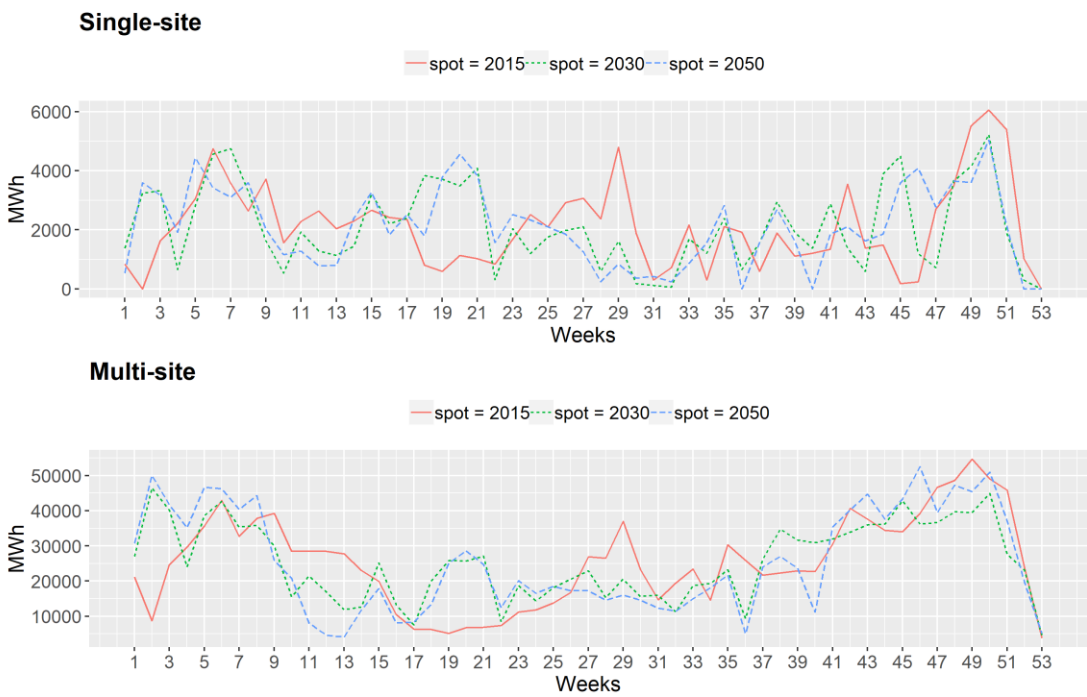
Figures A 1: Generation without (= spot) and with SRL (30MW in week 17) for symmetric and asymmetric weekly products.



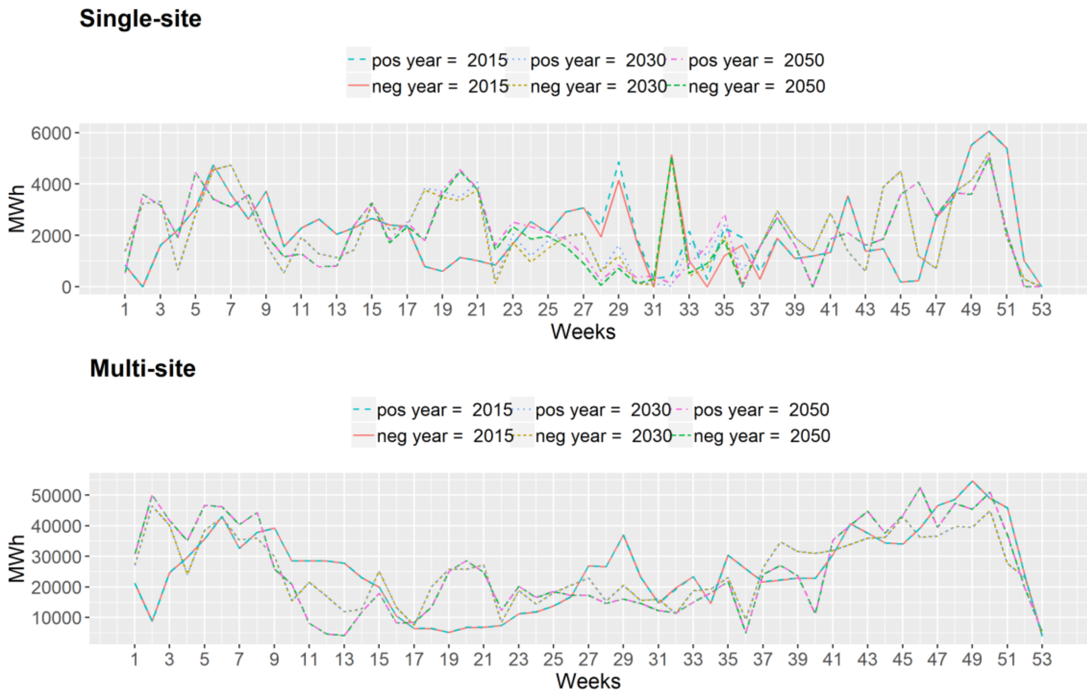
Figures A 2: Generation without (= spot) and with SRL (30MW in week 17) for symmetric and asymmetric weekly and daily products.



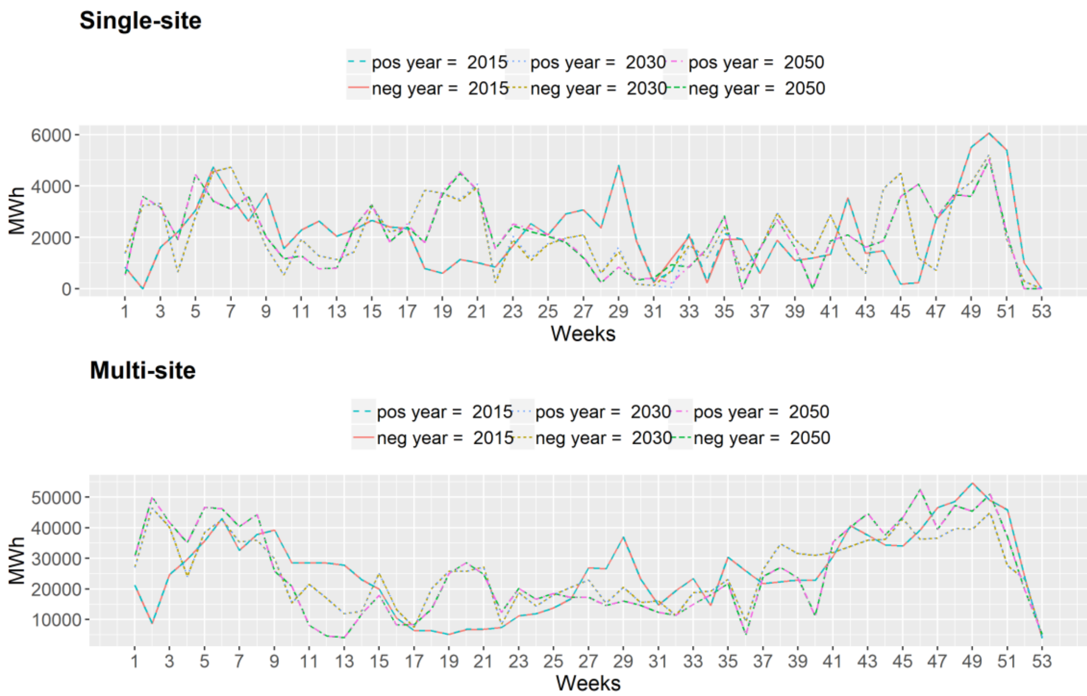
Figures A 3: Generation spot (= no SRL) for 2015, 2030 and 2050.



Figures A 4: Generation with SRL (30MW in week 32) for asymmetric weekly products and different years.

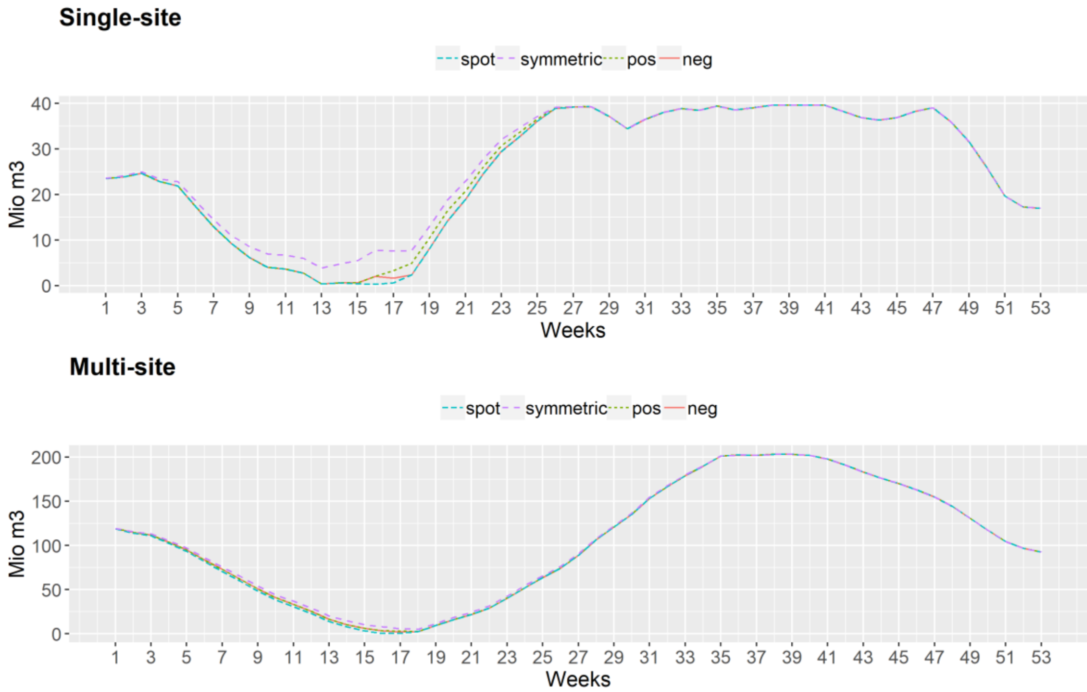


Figures A 5: Generation with SRL (30MW in week 32) for asymmetric daily products and different years.

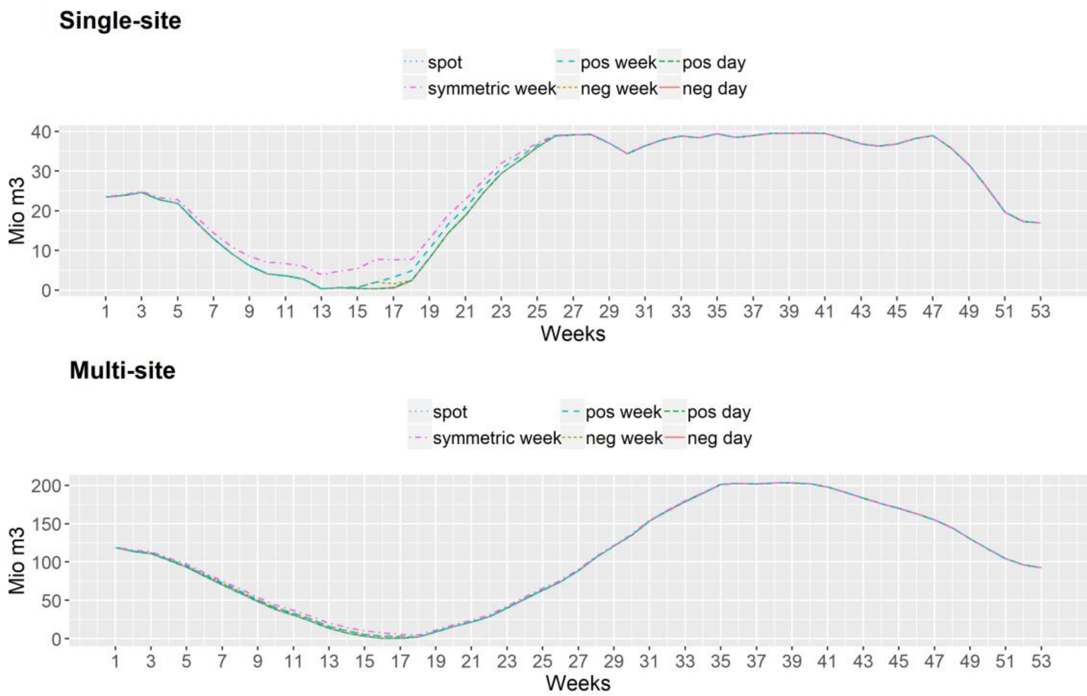


A2.2 Storage

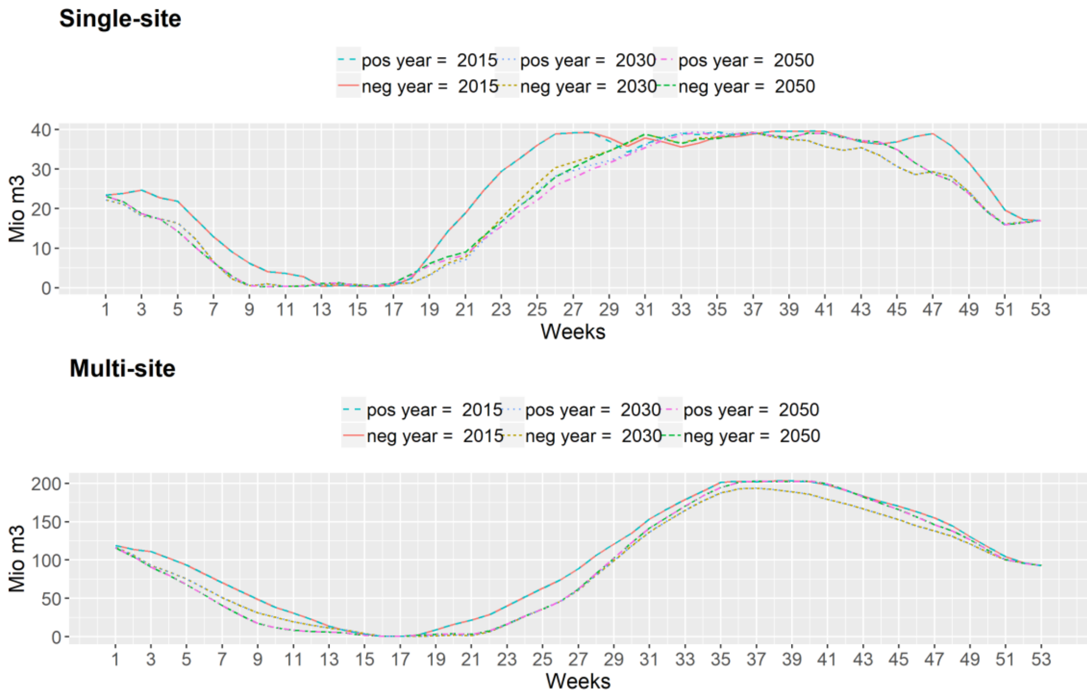
Figures A 6: Average storage level without (= spot) and with SRL (30MW in week 17) for asymmetric weekly products.



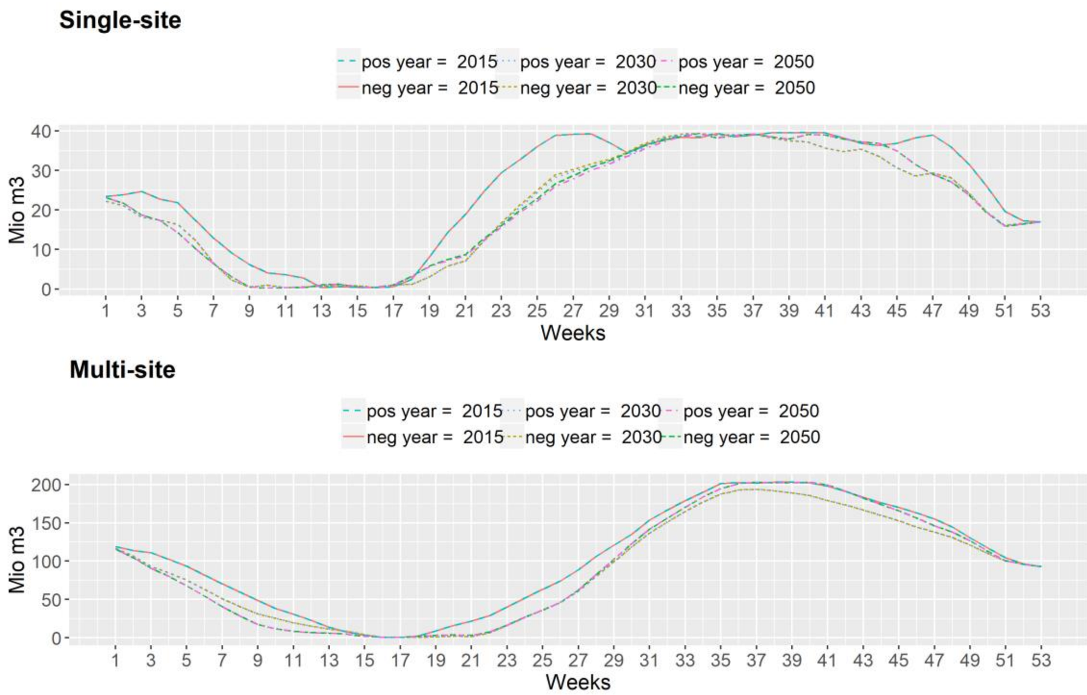
Figures A 7: Average storage level without (= spot) and with SRL (30MW in week 17) for asymmetric weekly and daily products.



Figures A 8: Average storage level with SRL (30MW in week 32) for asymmetric weekly products and different years.

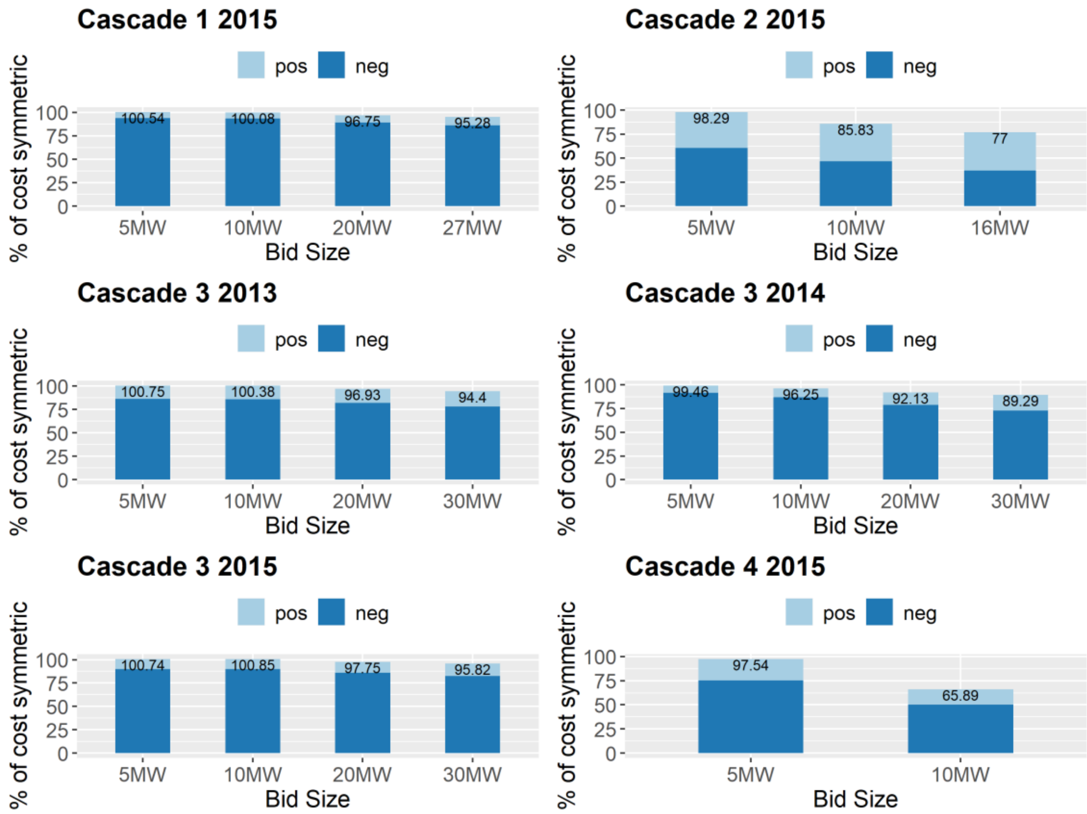


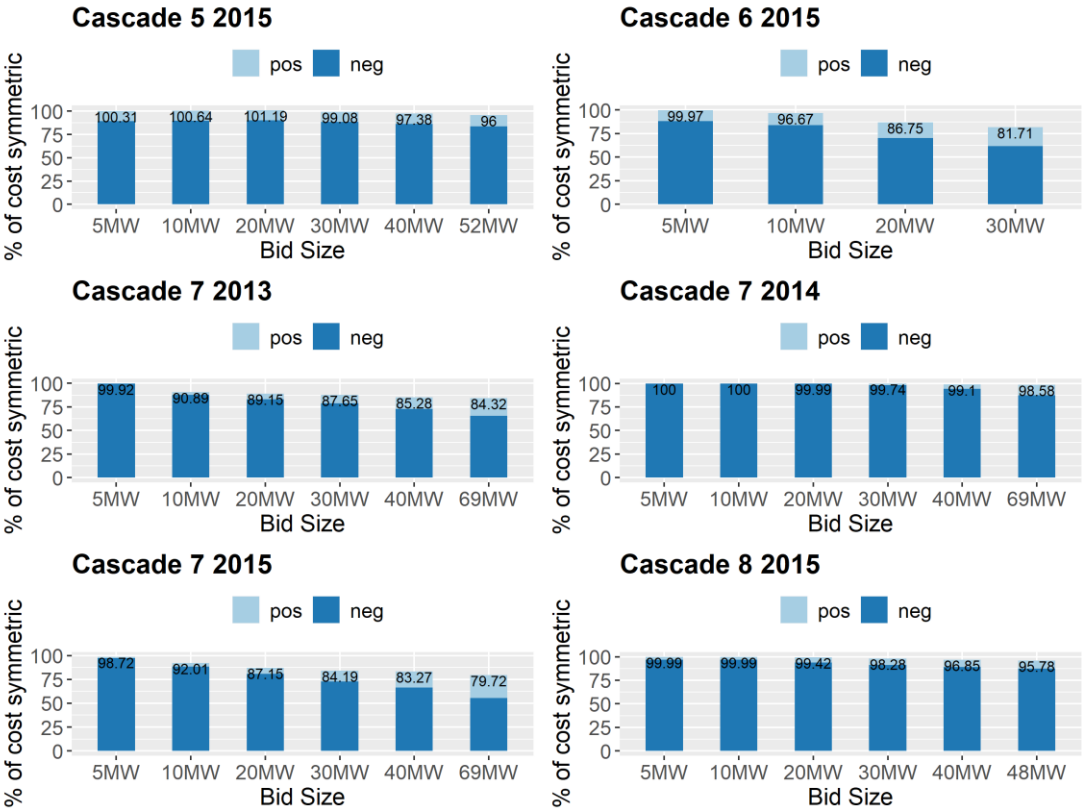
Figures A 9: Average storage level with SRL (30MW in week 32) for asymmetric daily products and different years.



A2.3 Cost - Symmetric vs. asymmetric products

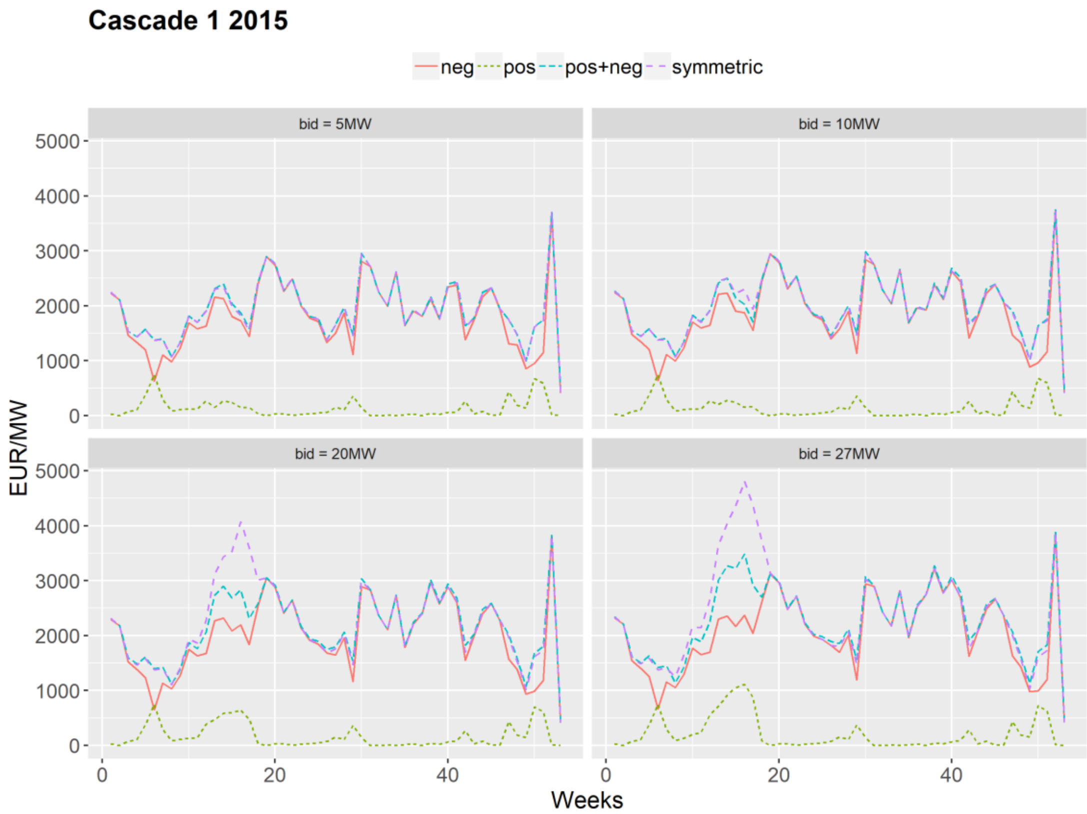
Figures A 10: Cost per year for asymmetric weekly SRL relative to symmetric weekly SRL by bid size, cascade and year.

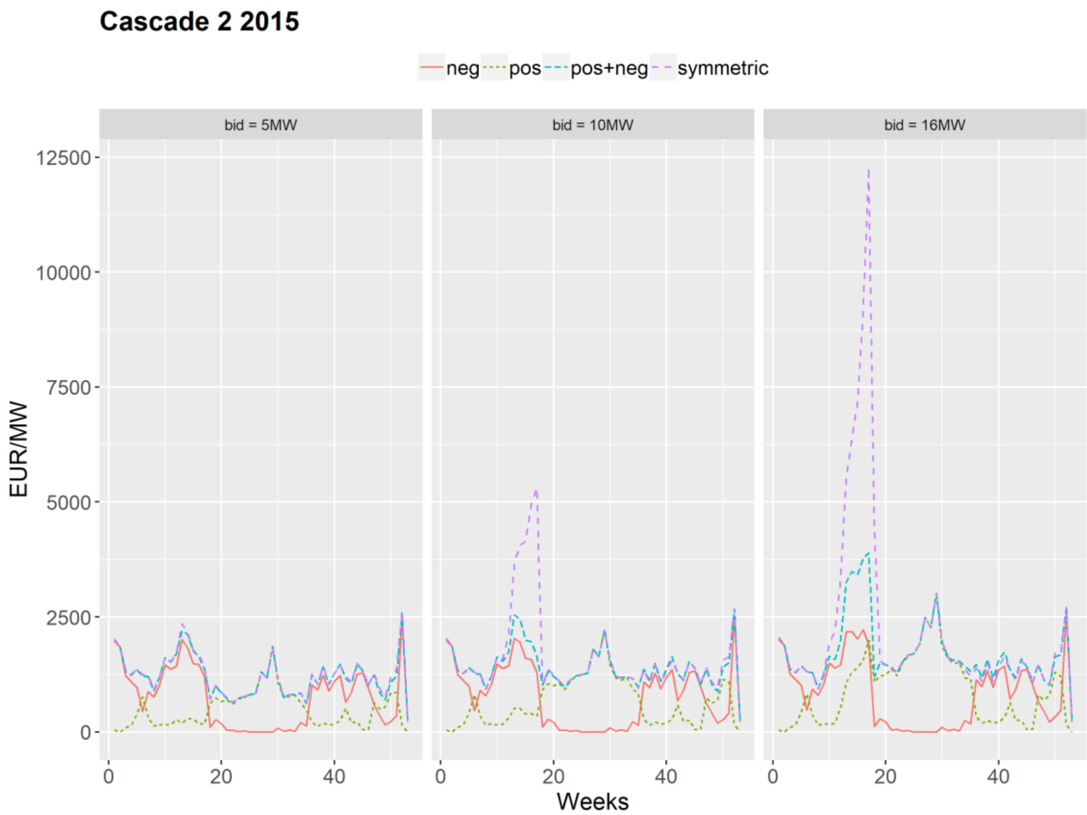


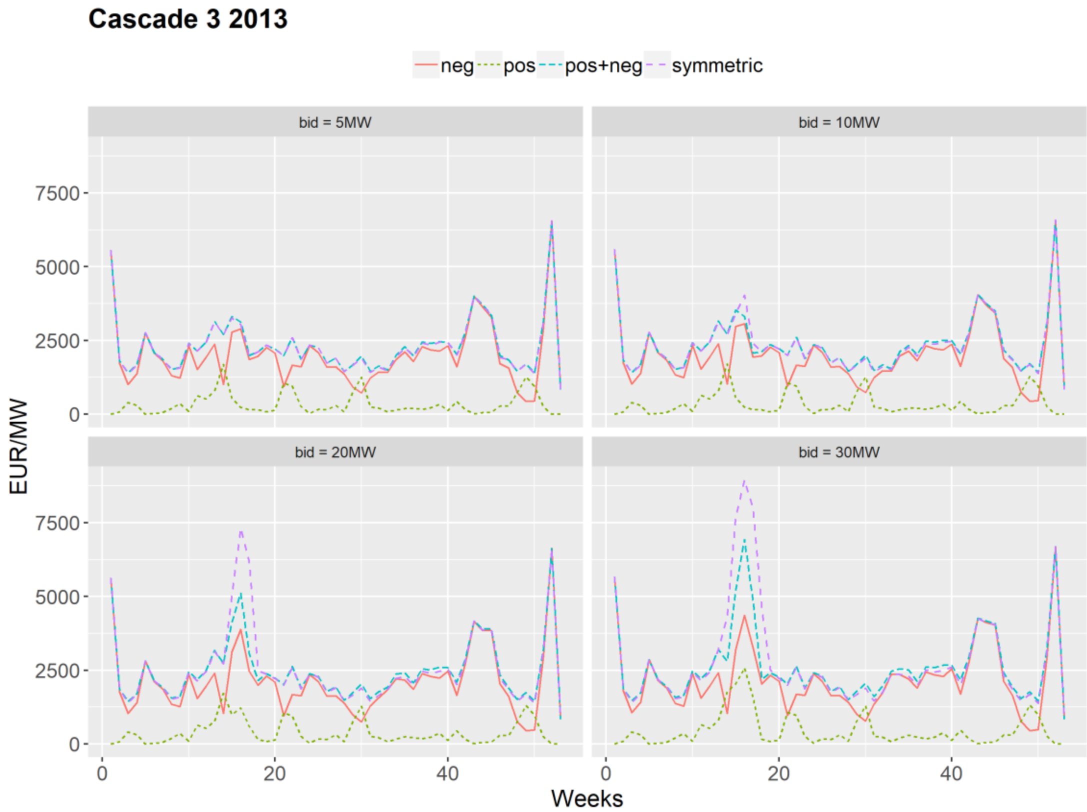


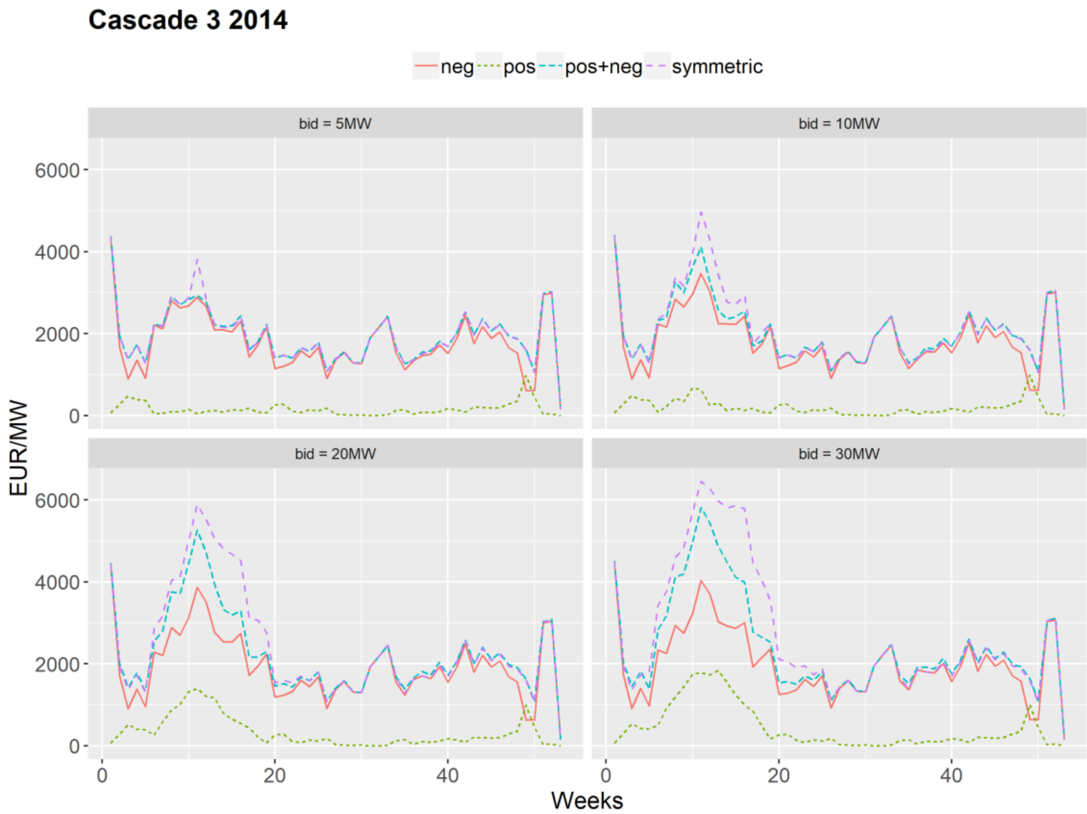
Cascade 5 2015
pos
neg
% of cost symmetric
100
75
50
25
0
100.31
100.64
101.19
99.08
97.38
96
5MW
10MW
20MW
30MW
40MW
52MW
Bid Size
Cascade 6 2015
pos
neg
% of cost symmetric
100
75
50
25
0
99.97
96.67
86.75
81.71
5MW
10MW
20MW
30MW
Bid Size
Cascade 7 2013
pos
neg
% of cost symmetric
100
75
50
25
0
99.92
90.89
89.15
87.65
85.28
84.32
5MW
10MW
20MW
30MW
40MW
69MW
Bid Size
Cascade 7 2014
pos
neg
% of cost symmetric
100
75
50
25
0
100
100
99.99
99.74
99.1
98.58
5MW
10MW
20MW
30MW
40MW
69MW
Bid Size
Cascade 7 2015
pos
neg
% of cost symmetric
100
75
50
25
0
98.72
92.01
87.15
84.19
83.27
79.72
5MW
10MW
20MW
30MW
40MW
69MW
Bid Size
Cascade 8 2015
pos
neg
% of cost symmetric
100
75
50
25
0
99.99
99.99
99.42
98.28
96.85
95.78
5MW
10MW
20MW
30MW
40MW
48MW
Bid Size

Figures A 11: Opportunity cost for weekly symmetric and asymmetric SRL by cascade, bid size and year.

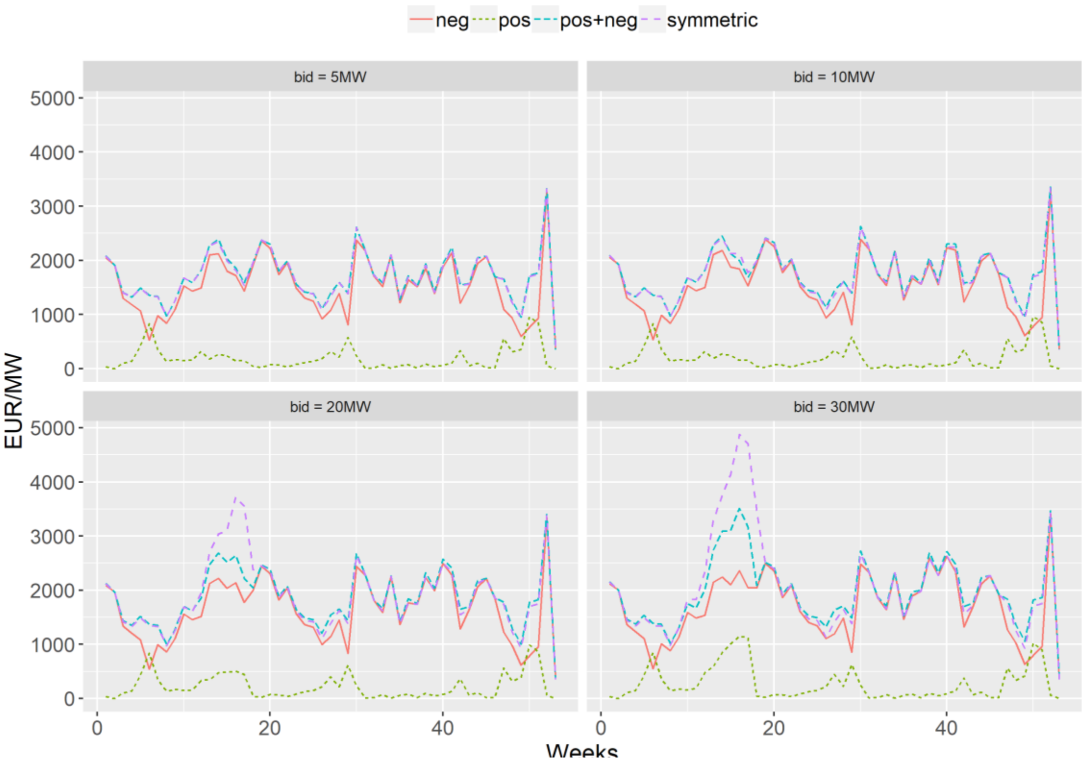




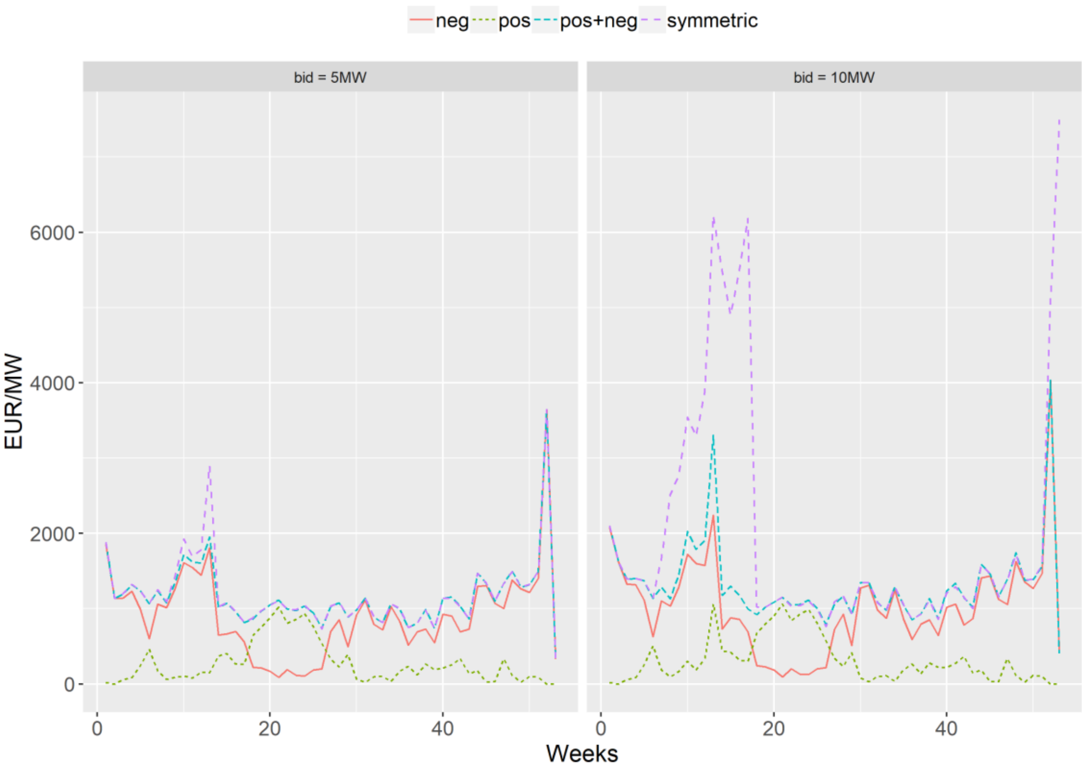

Cascade 3 2013
neg
pos
pos+neg
symmetric
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
EUR/MW
7500
5000
2500
0
0
20
40
Weeks

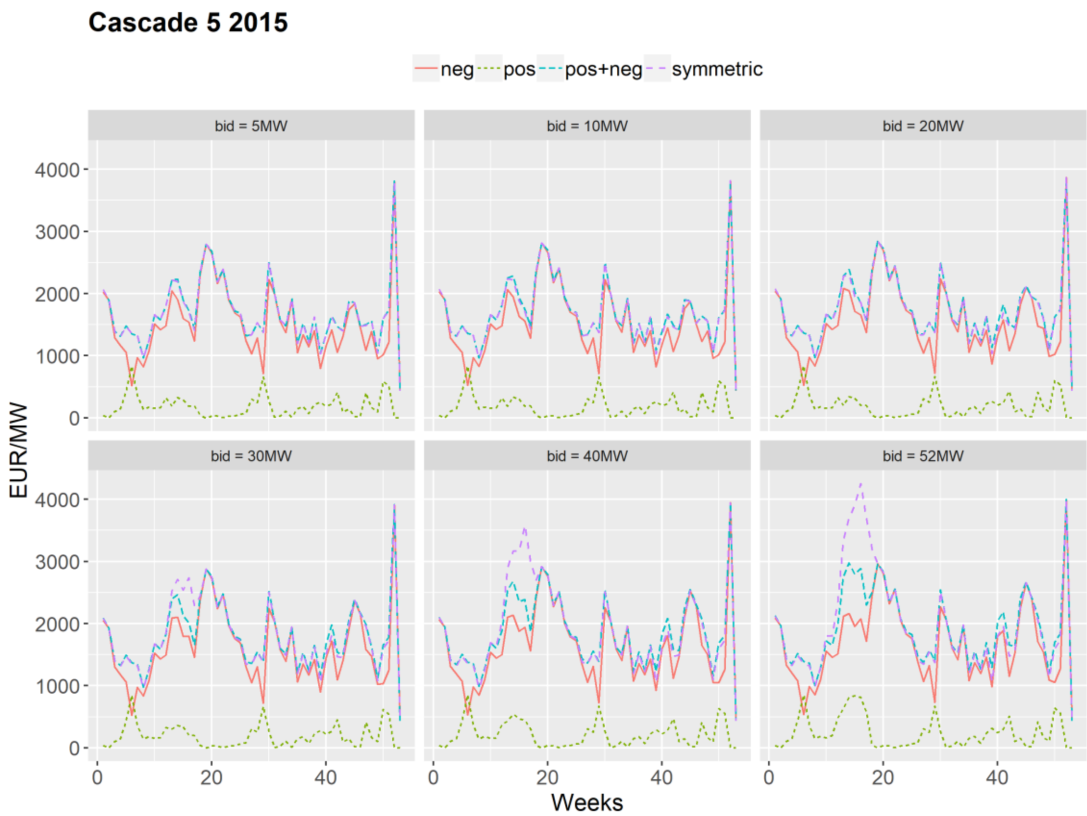

Cascade 3 2014
neg
pos
pos+neg
symmetric
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
EUR/MW
6000
4000
2000
0
0
20
40
Weeks

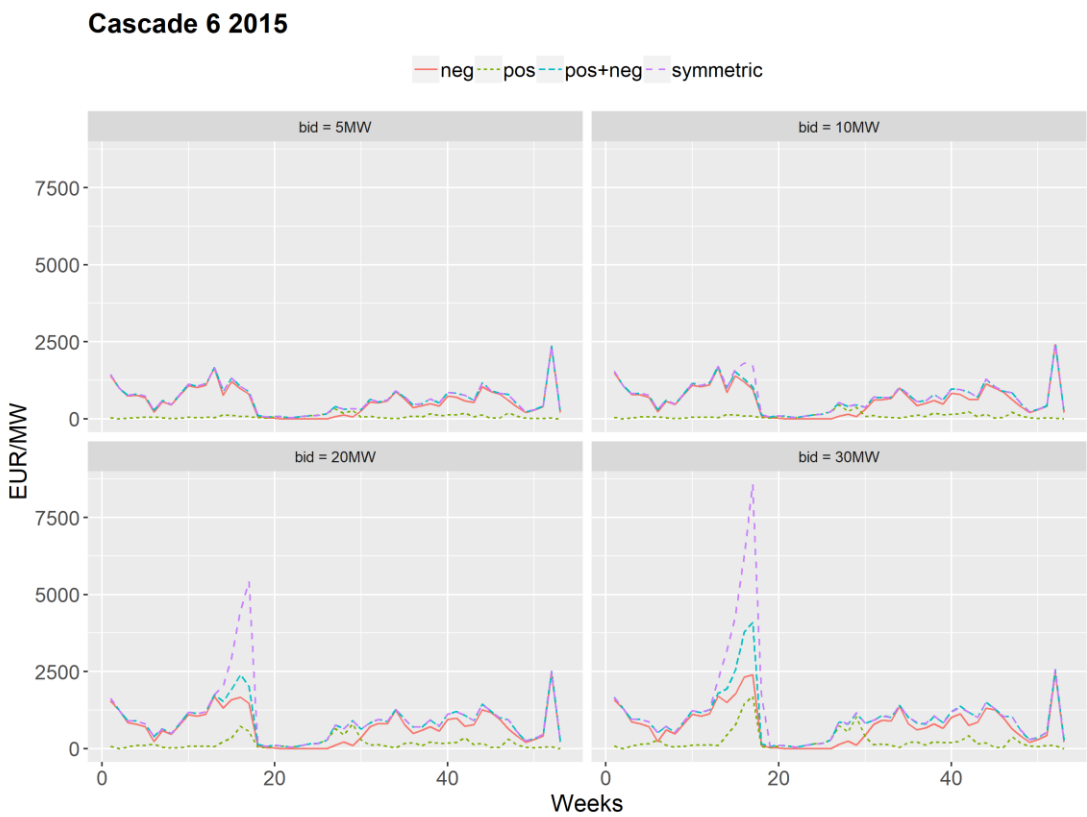
Cascade 3 2015

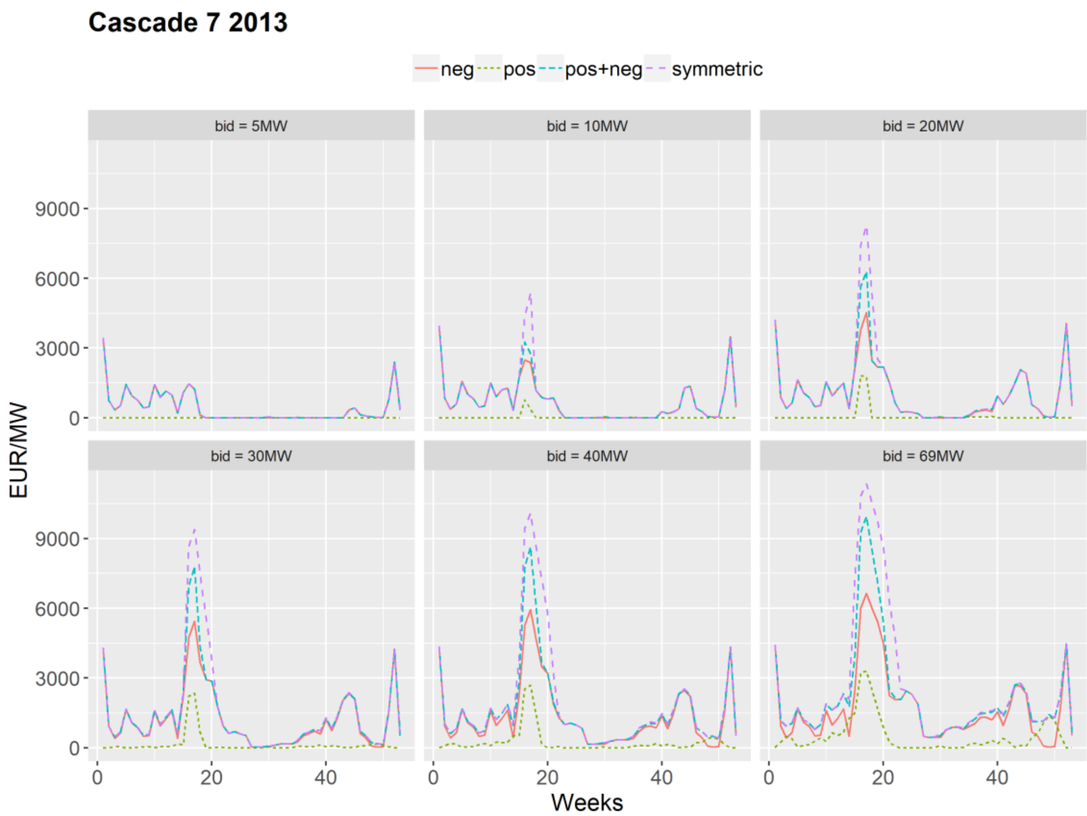


Cascade 4 2015

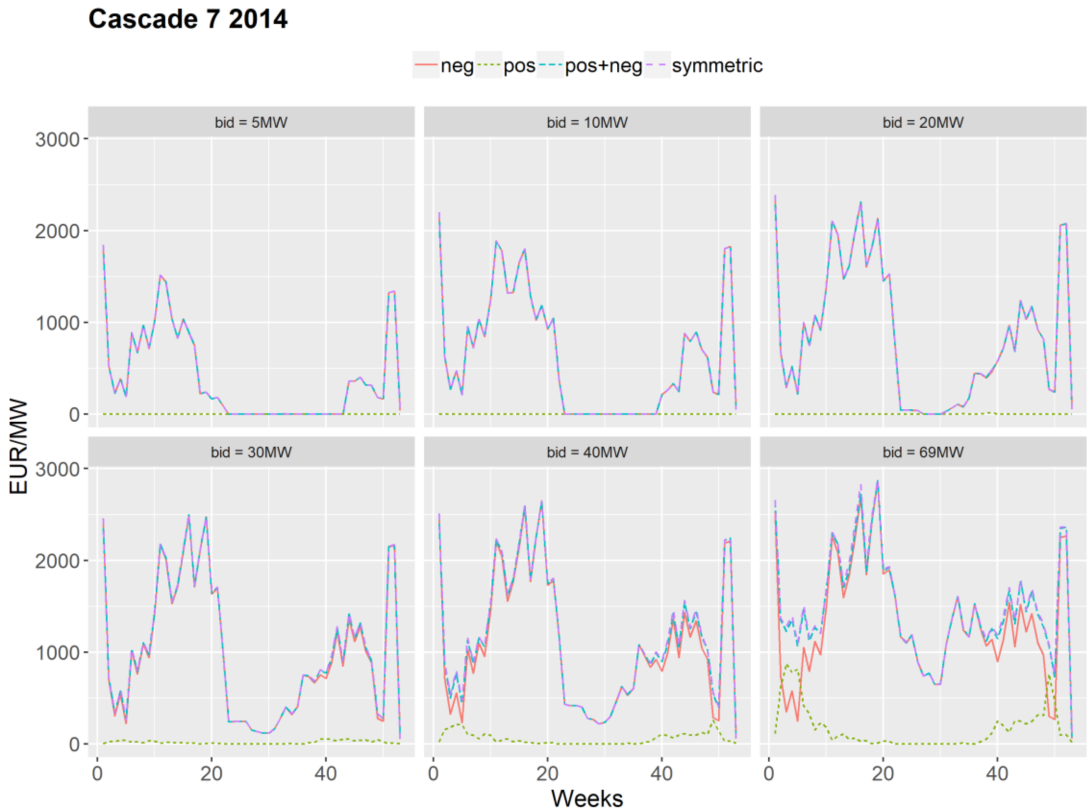



Cascade 5 2015
neg pos pos+neg symmetric
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 52MW
EUR/MW
Weeks

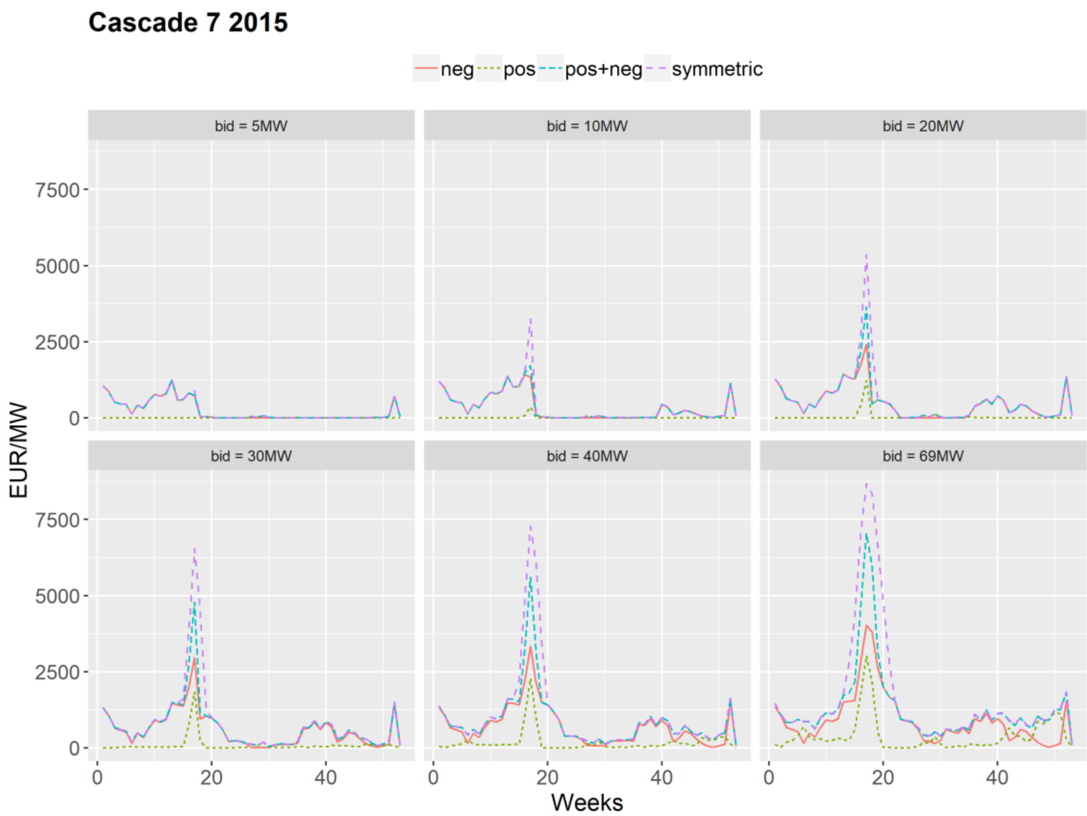

Cascade 6 2015
neg pos pos+neg symmetric
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
EUR/MW
Weeks

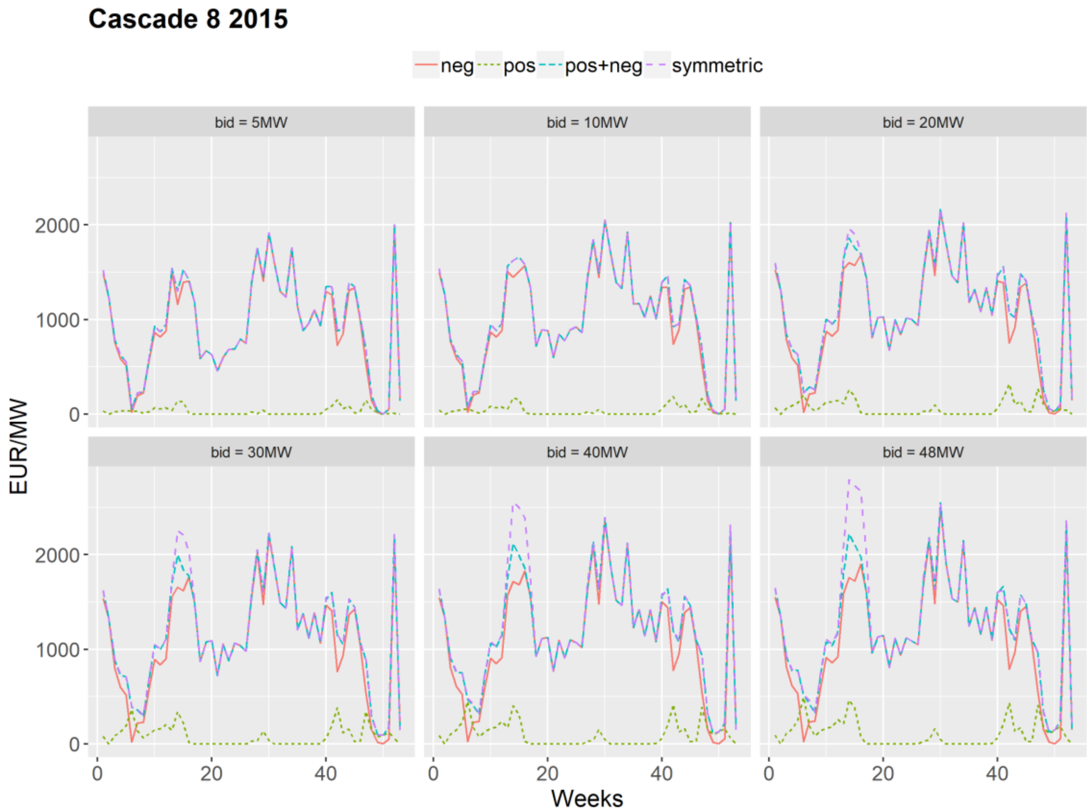


Cascade 7 2013
neg
pos
pos+neg
symmetric
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 69MW
EUR/MW
Weeks



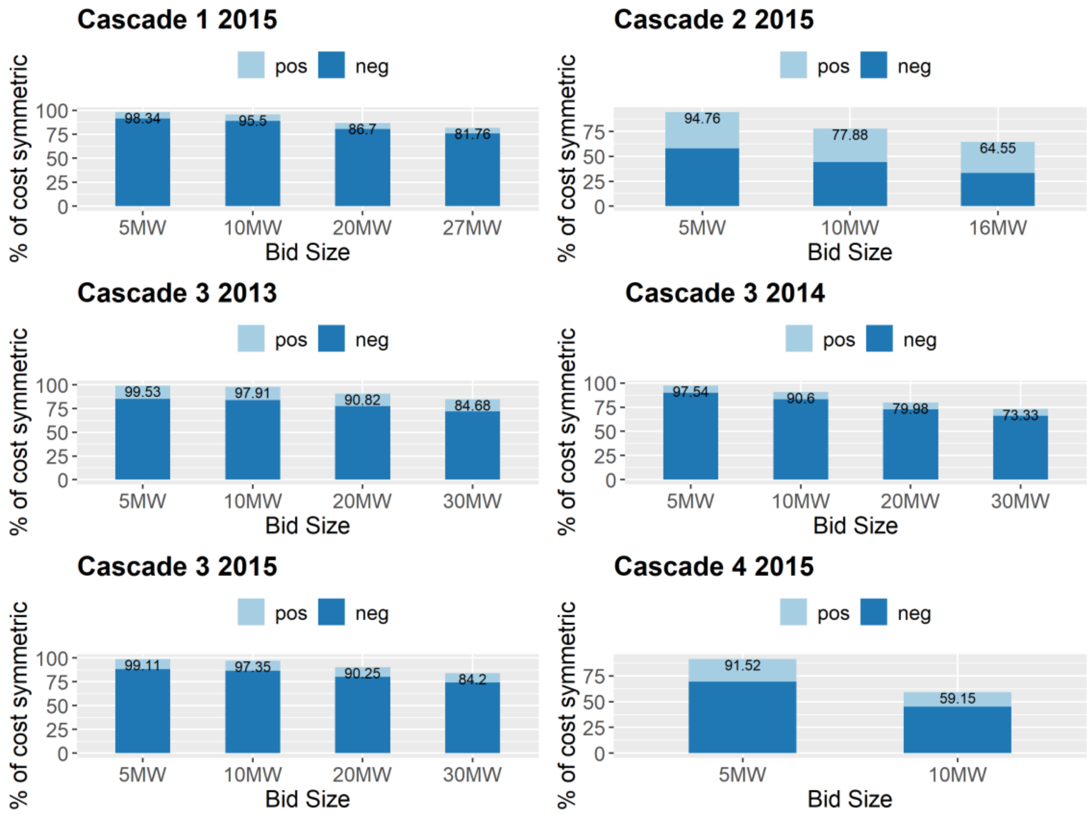
Cascade 7 2014
neg
pos
pos+neg
symmetric
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 69MW
EUR/MW
Weeks

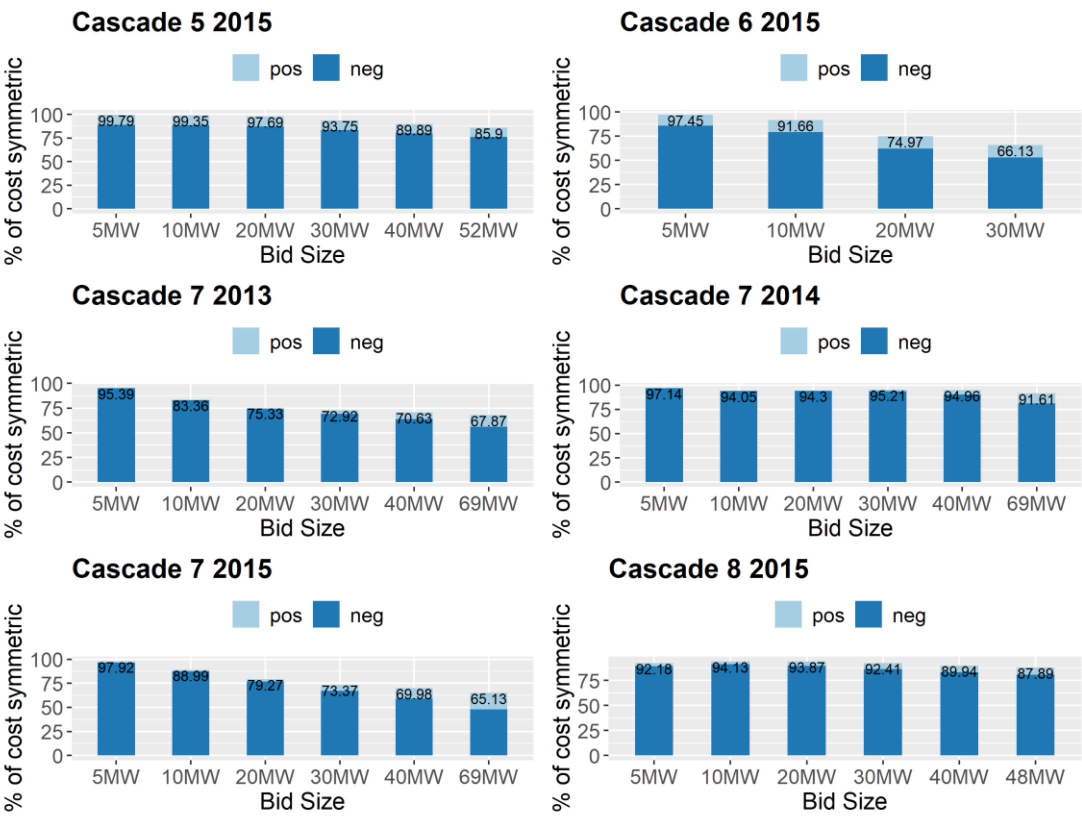

Cascade 7 2015
neg
pos
pos+neg
symmetric
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 69MW
EUR/MW
7500
5000
2500
0
20
40
Weeks


Cascade 8 2015
neg
pos
pos+neg
symmetric
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 48MW
EUR/MW
2000
1000
0
20
40
Weeks

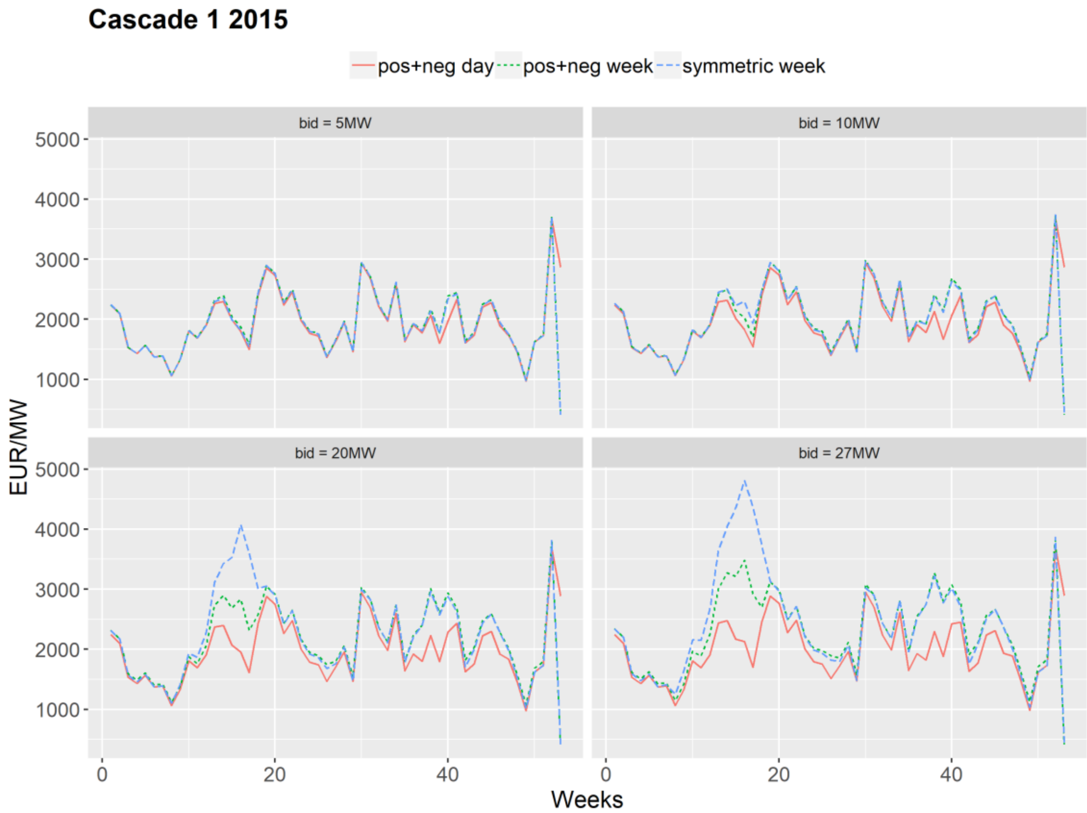
A2.4 Cost - Daily products

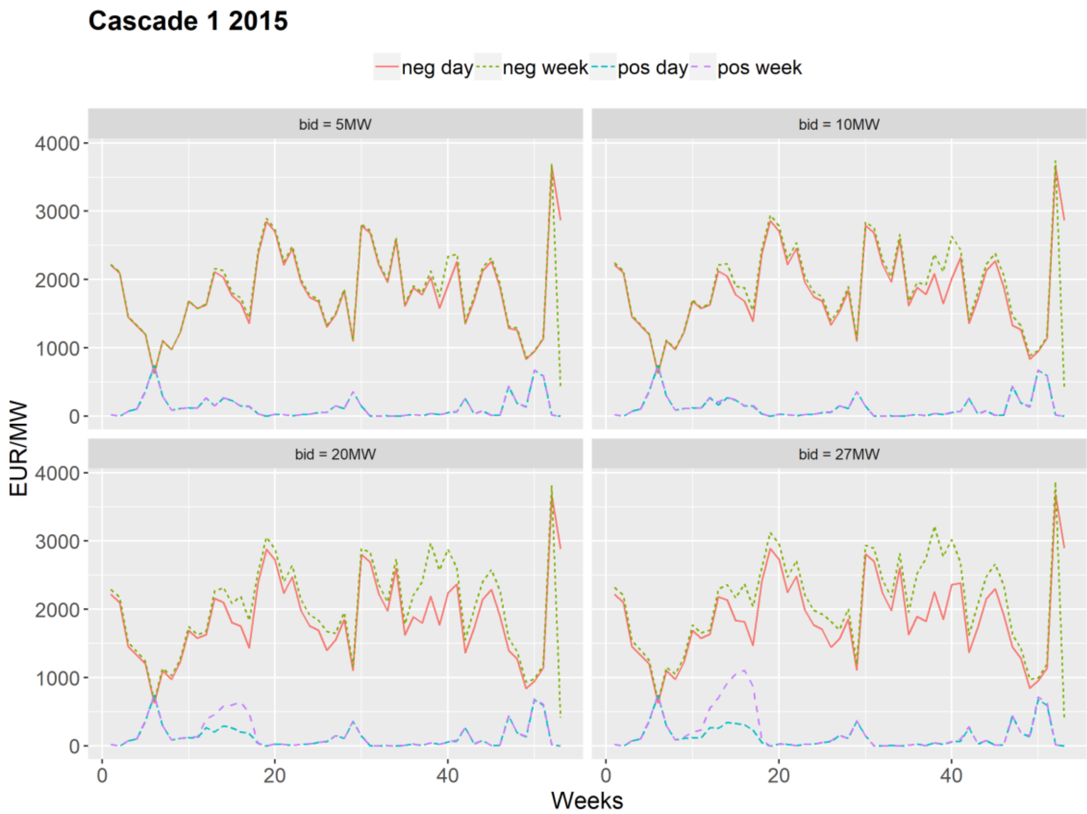
Figures A 12: Cost per year for asymmetric daily SRL relative to symmetric weekly SRL by bid size, cascade and year.

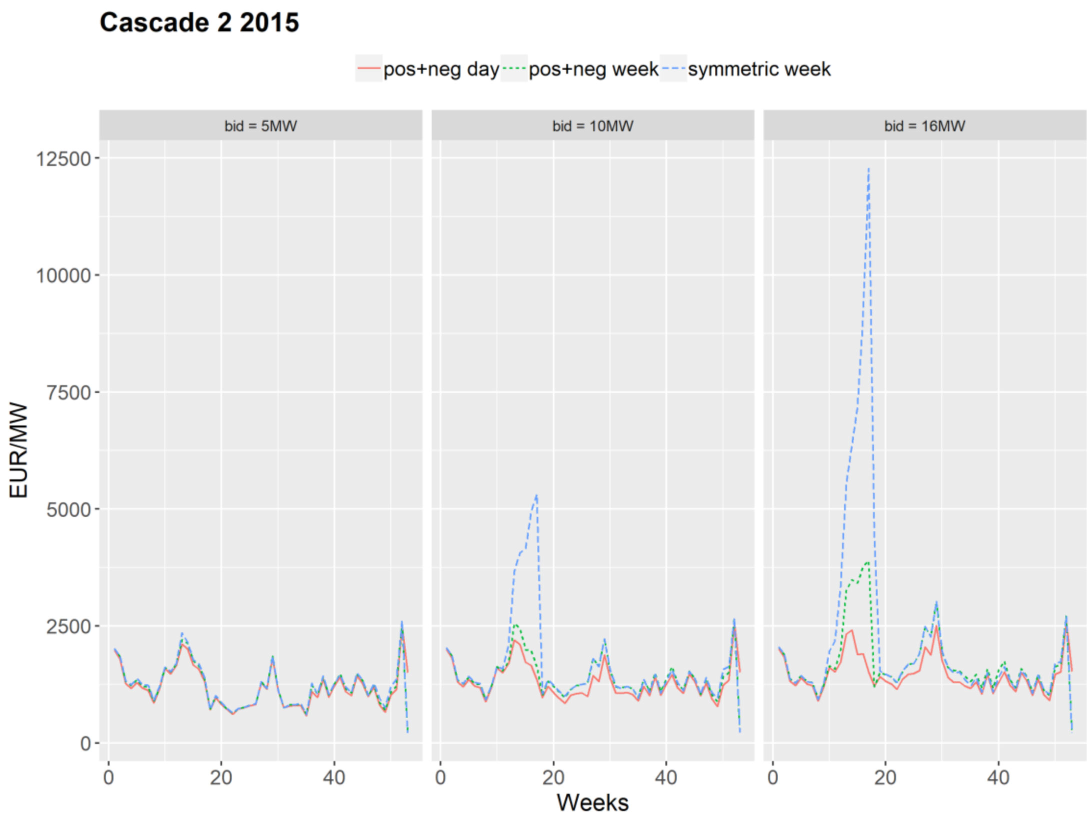


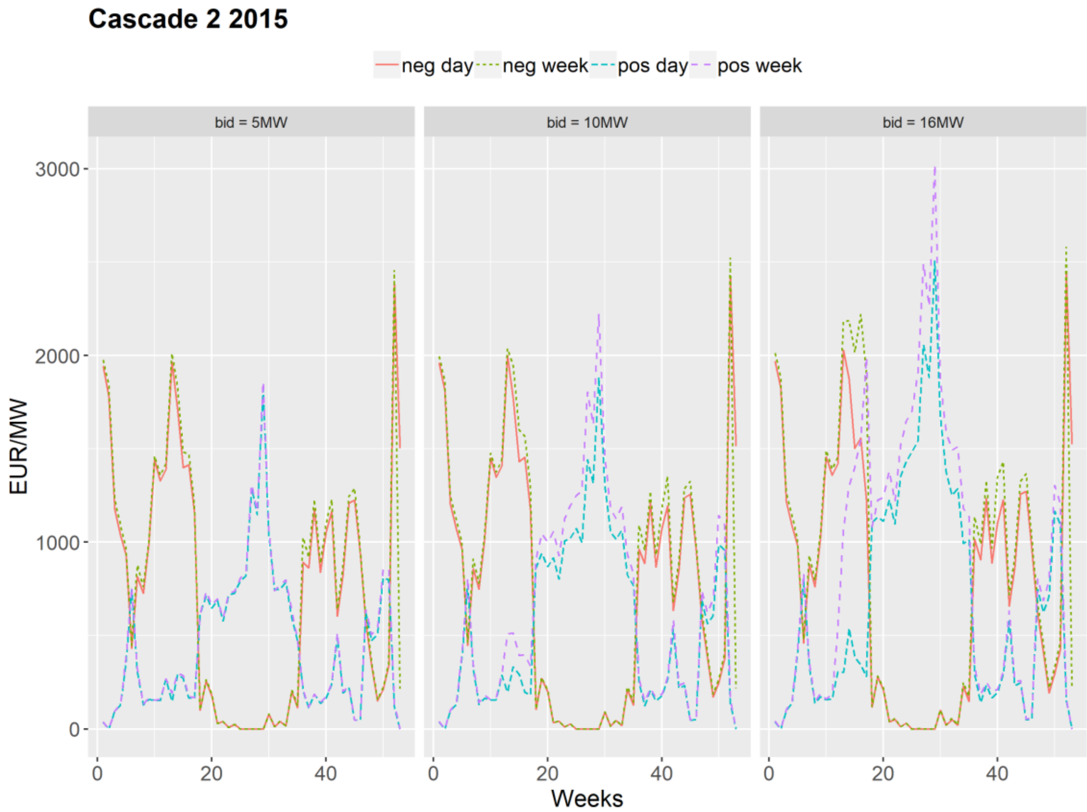

Cascade 5 2015
pos neg
% of cost symmetric
100 75 50 25 0
99.79 99.35 97.69 93.75 89.89 85.9
5MW 10MW 20MW 30MW 40MW 52MW
Bid Size
Cascade 6 2015
pos neg
% of cost symmetric
100 75 50 25 0
97.45 91.66 74.97 66.13
5MW 10MW 20MW 30MW
Bid Size
Cascade 7 2013
pos neg
% of cost symmetric
100 75 50 25 0
95.39 83.36 75.33 72.92 70.63 67.87
5MW 10MW 20MW 30MW 40MW 69MW
Bid Size
Cascade 7 2014
pos neg
% of cost symmetric
100 75 50 25 0
97.14 94.05 94.3 95.21 94.96 91.61
5MW 10MW 20MW 30MW 40MW 69MW
Bid Size
Cascade 7 2015
pos neg
% of cost symmetric
100 75 50 25 0
97.92 88.99 79.27 73.37 69.98 65.13
5MW 10MW 20MW 30MW 40MW 69MW
Bid Size
Cascade 8 2015
pos neg
% of cost symmetric
75 50 25 0
92.18 94.13 93.87 92.41 89.94 87.89
5MW 10MW 20MW 30MW 40MW 48MW
Bid Size

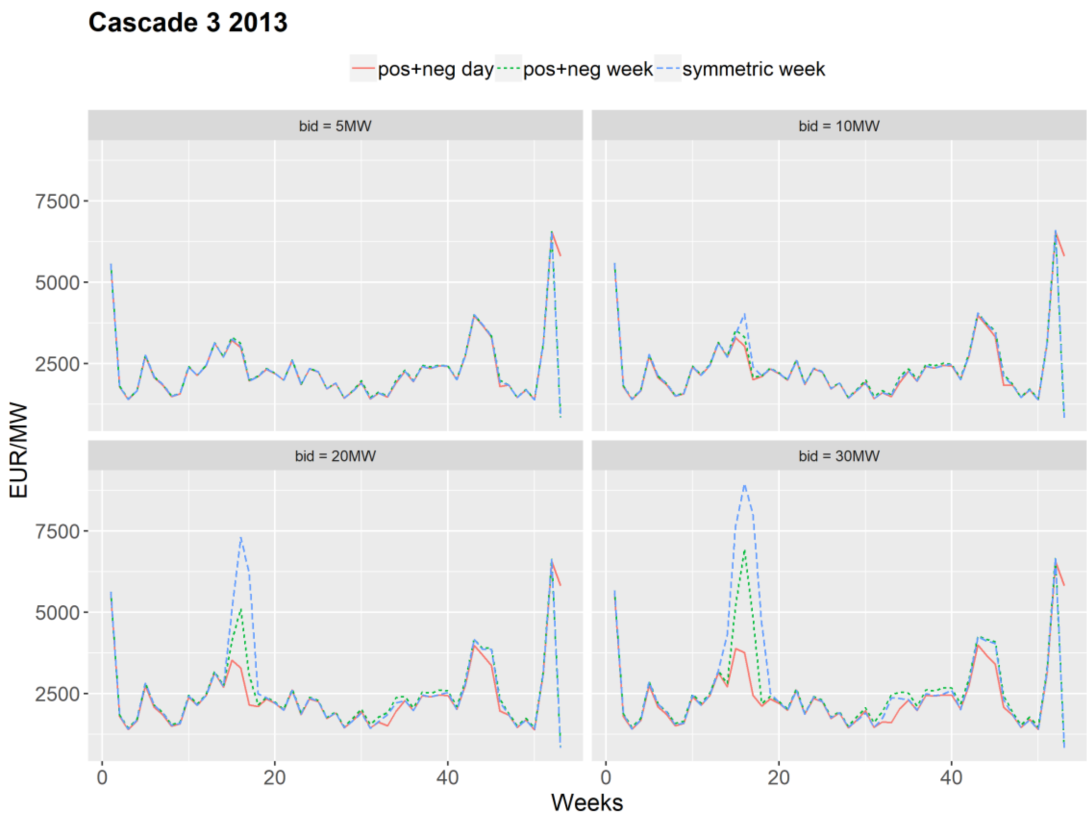
Figures A 13: Opportunity costs for symmetric and asymmetric SRL by duration, cascade, bid size and year. Top figure for each cascade shows the sum over positive and negative products, bottom figure for each cascade is split up by direction.

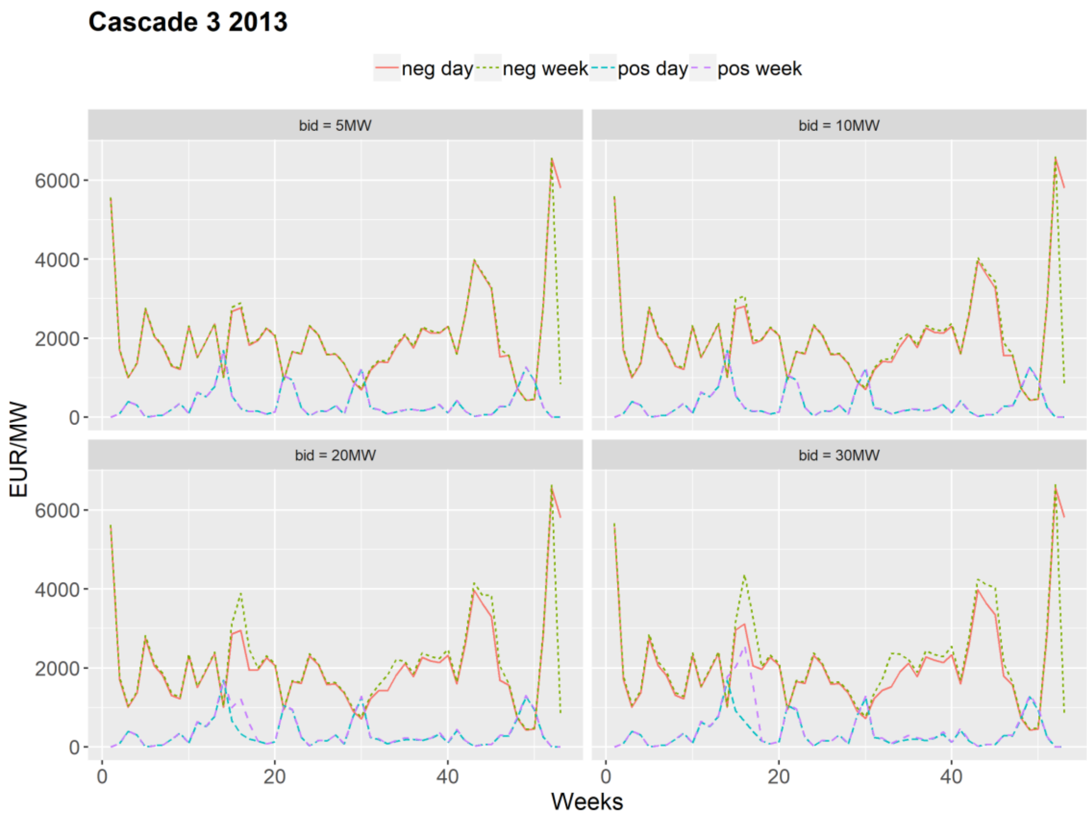


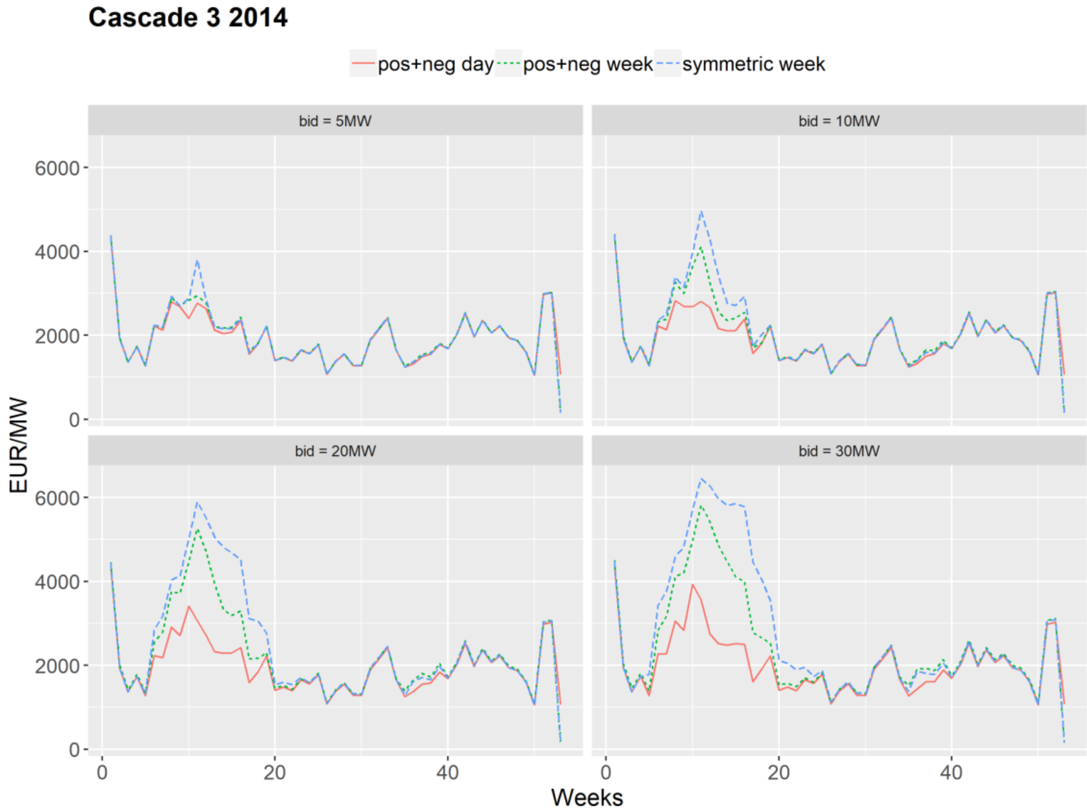


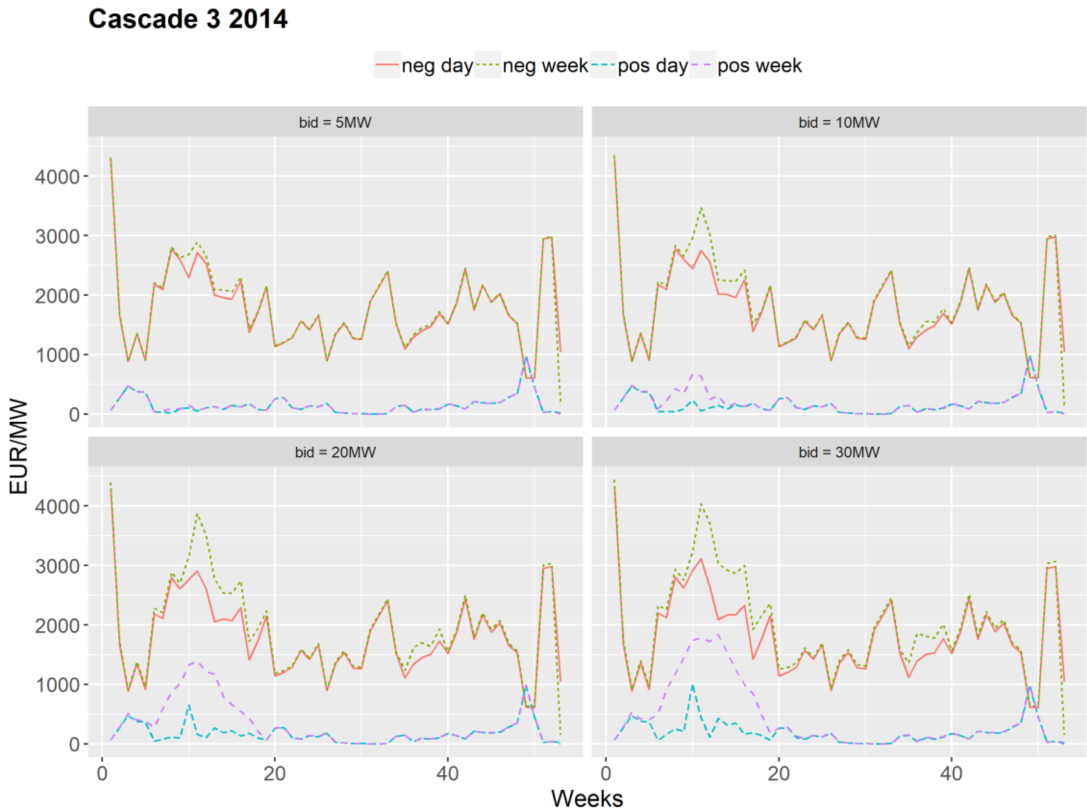

Cascade 2 2015
pos+neg day
pos+neg week
symmetric week
bid = 5MW
bid = 10MW
bid = 16MW
EUR/MW
12500
10000
7500
5000
2500
0
20
40
Weeks

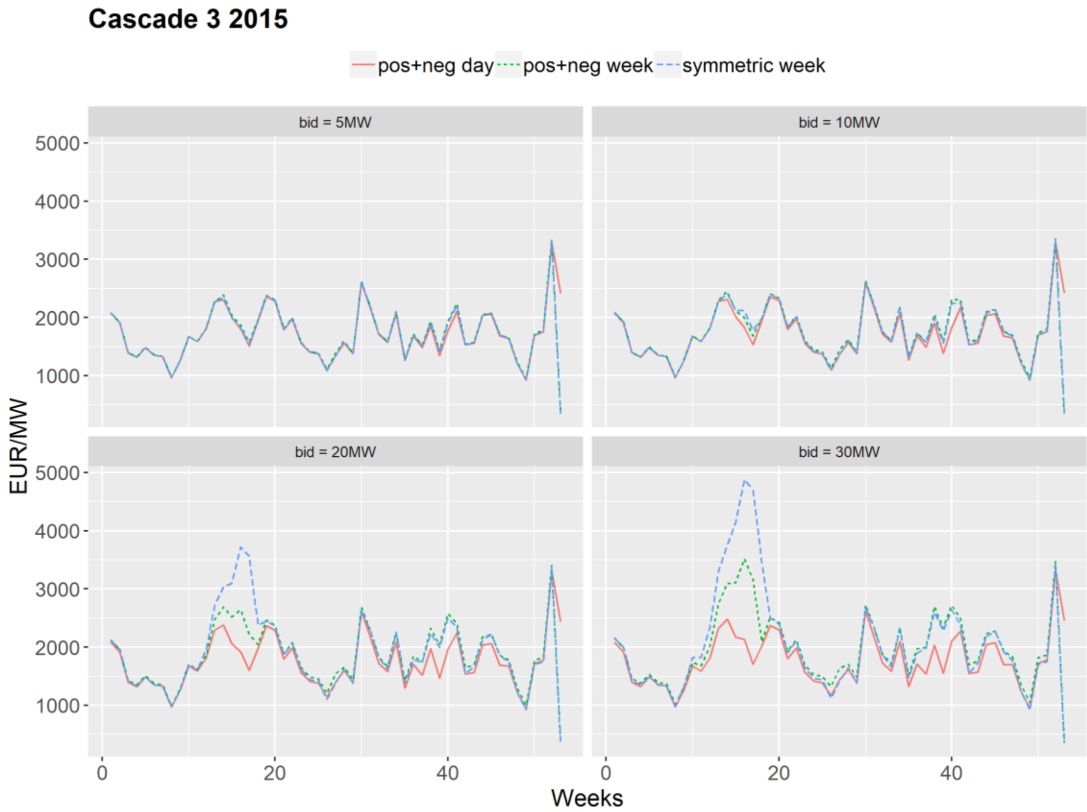

Cascade 2 2015
neg day
neg week
pos day
pos week
bid = 5MW
bid = 10MW
bid = 16MW
EUR/MW
3000
2000
1000
0
20
40
Weeks

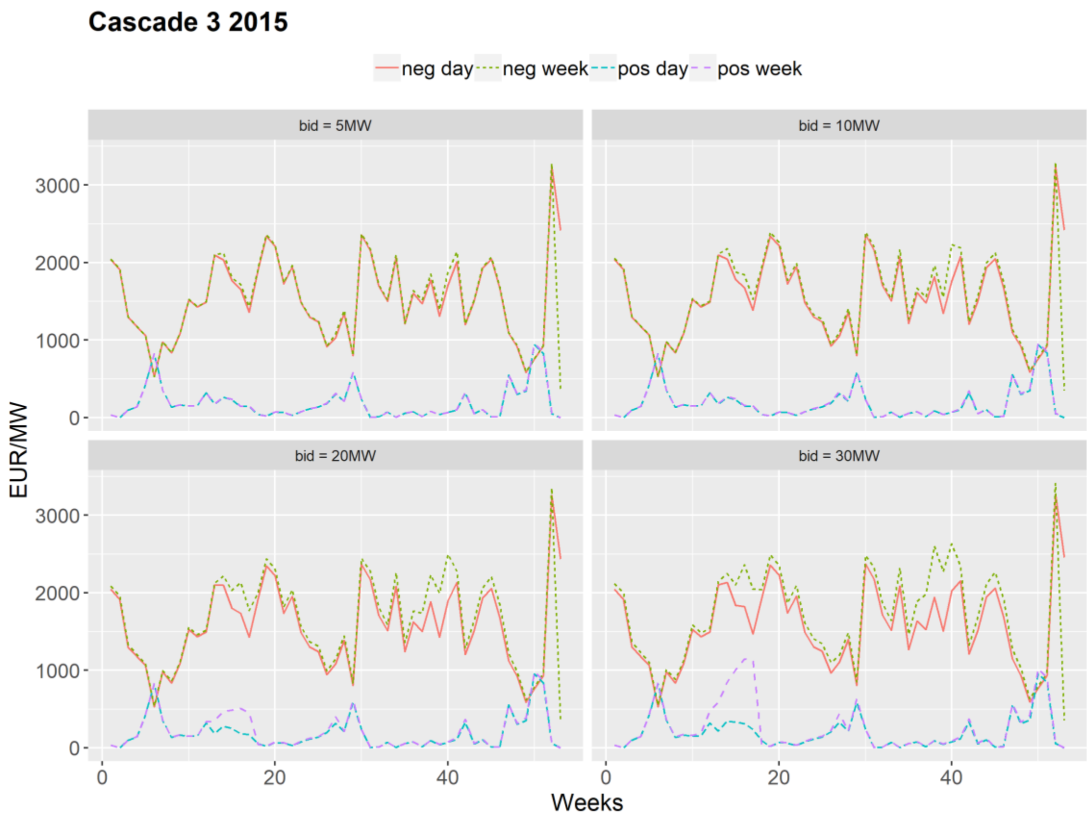

Cascade 3 2013
pos+neg day
pos+neg week
symmetric week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
EUR/MW
7500
5000
2500
0
20
40
Weeks

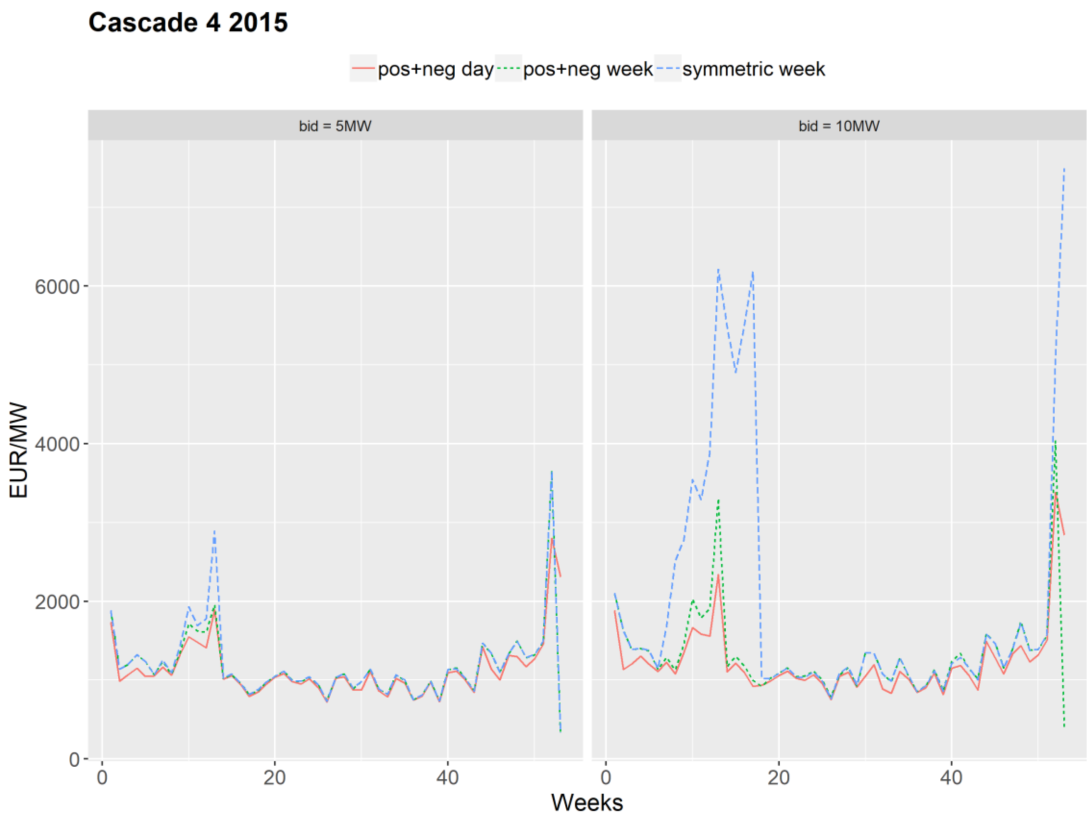

Cascade 3 2013
neg day
neg week
pos day
pos week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
EUR/MW
6000
4000
2000
0
20
40
Weeks

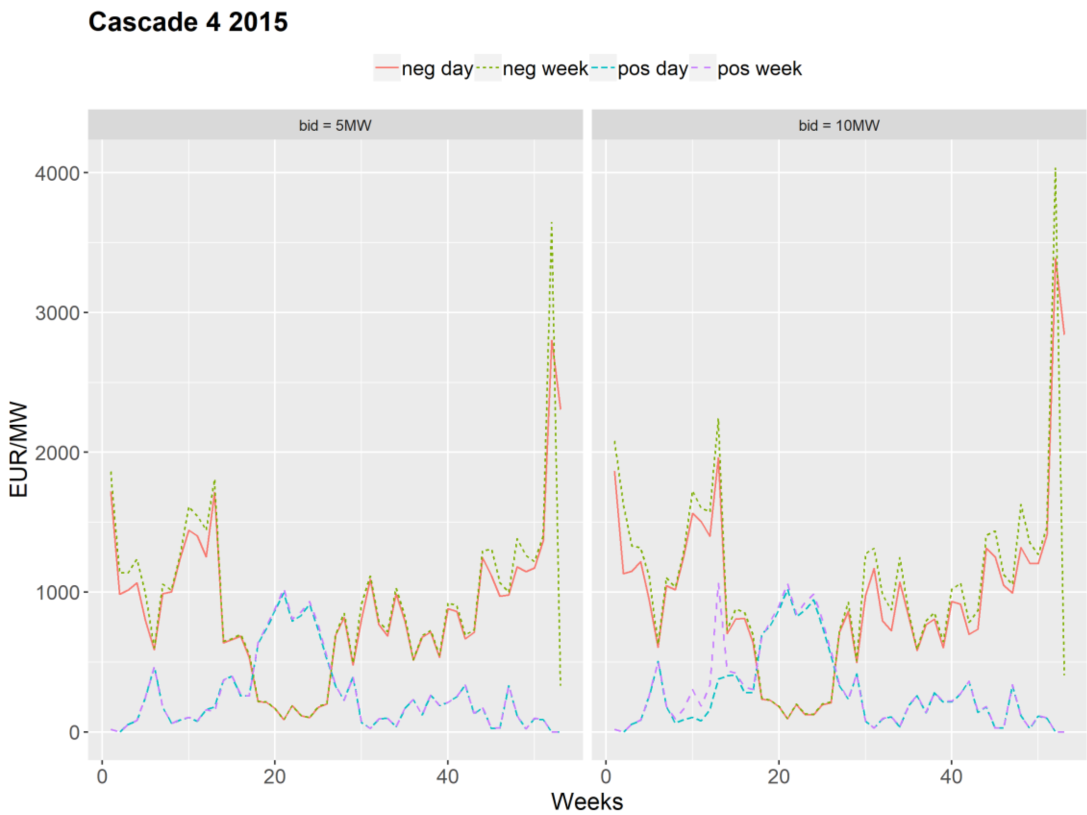

Cascade 3 2014
pos+neg day
pos+neg week
symmetric week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
EUR/MW
0
2000
4000
6000
0
20
40
Weeks

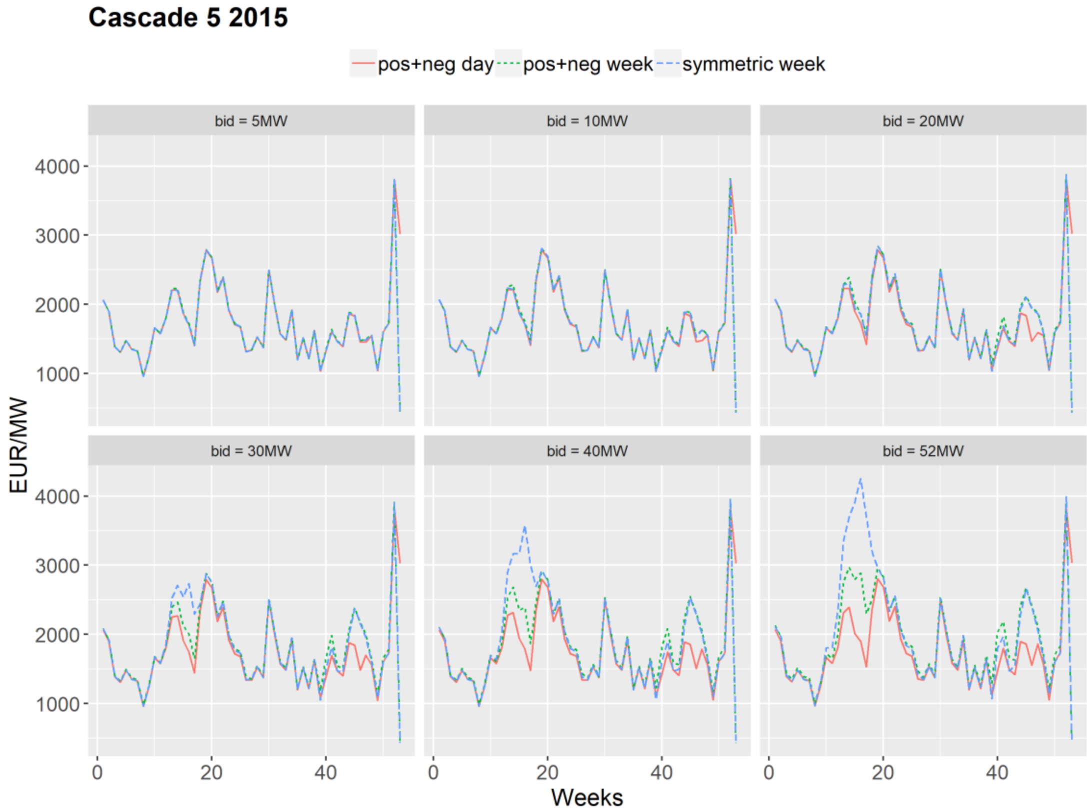

Cascade 3 2014
neg day
neg week
pos day
pos week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
EUR/MW
0
1000
2000
3000
4000
0
20
40
Weeks

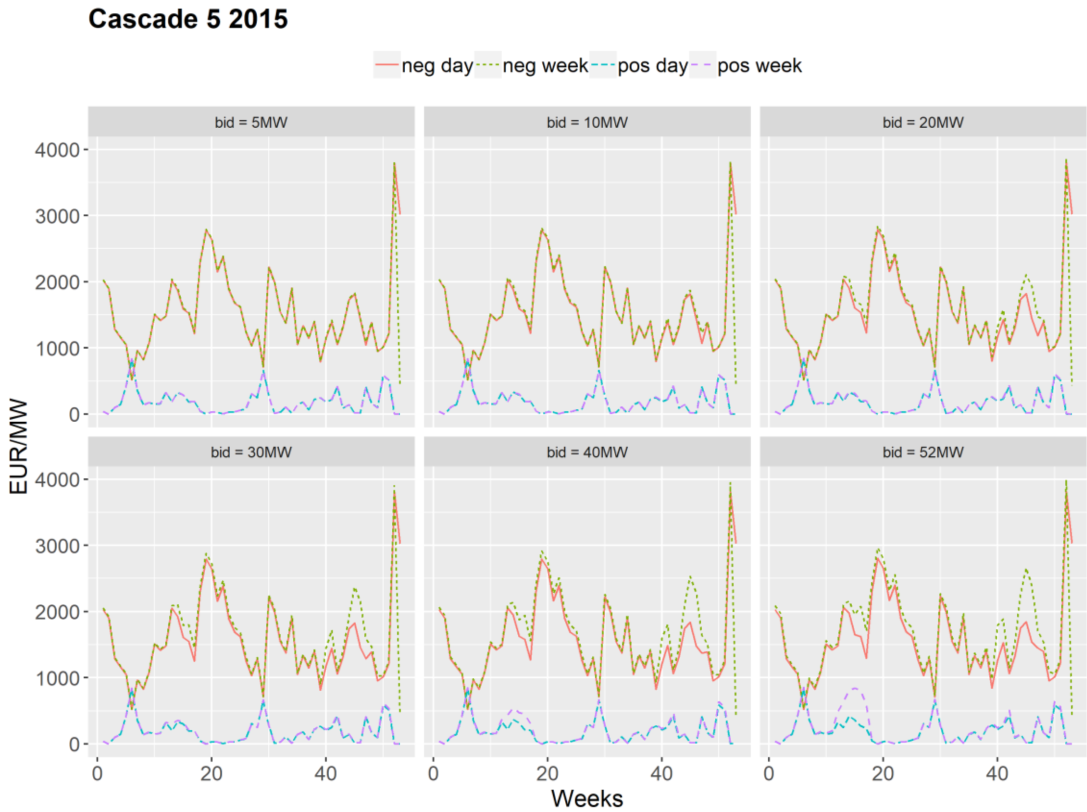

Cascade 3 2015
pos+neg day
pos+neg week
symmetric week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
EUR/MW
Weeks

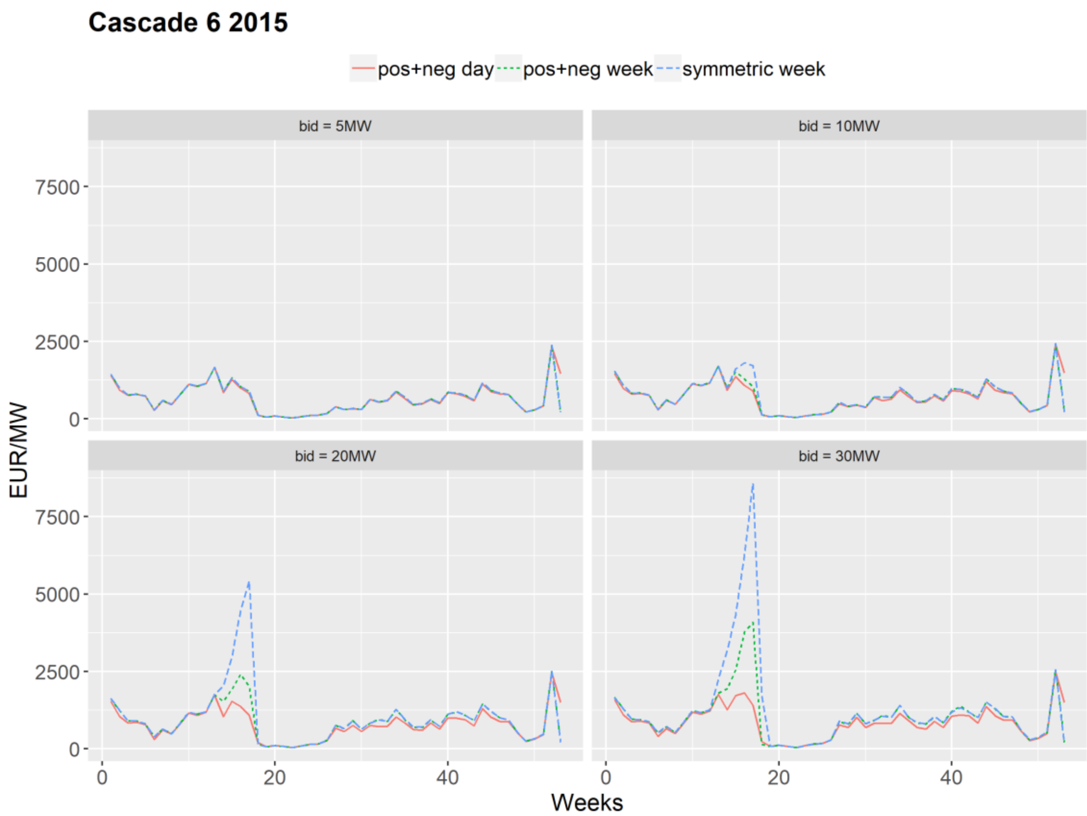

Cascade 3 2015
neg day
neg week
pos day
pos week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
EUR/MW
Weeks


Cascade 4 2015
pos+neg day
pos+neg week
symmetric week
bid = 5MW
bid = 10MW
EUR/MW
0
2000
4000
6000
0
20
40
Weeks

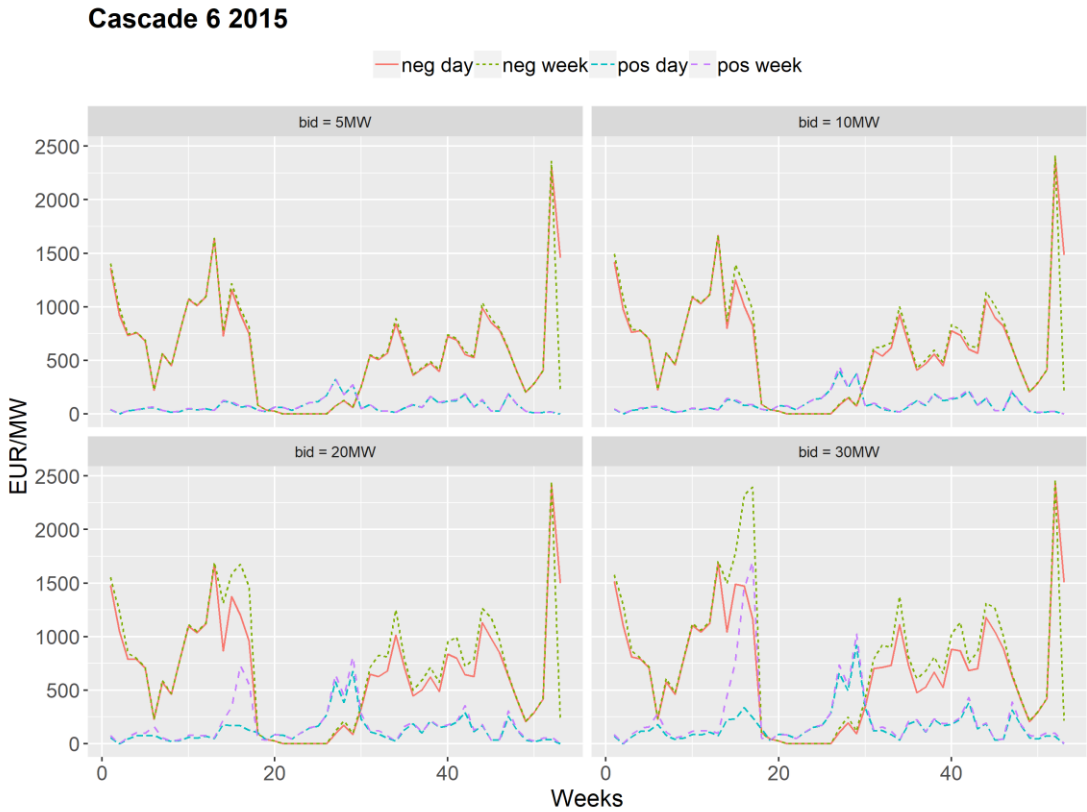

Cascade 4 2015
neg day
neg week
pos day
pos week
bid = 5MW
bid = 10MW
EUR/MW
0
1000
2000
3000
4000
0
20
40
Weeks


Cascade 5 2015
pos+neg day
pos+neg week
symmetric week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 52MW
EUR/MW
Weeks

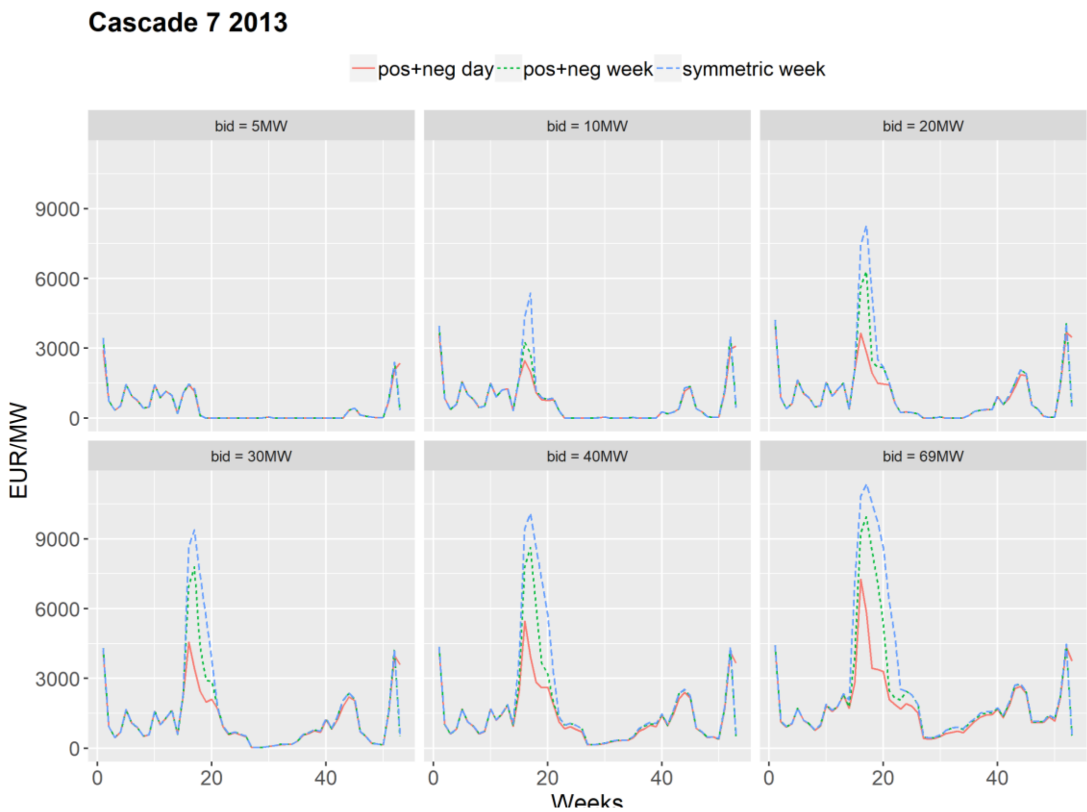

Cascade 5 2015
neg day
neg week
pos day
pos week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 52MW
EUR/MW
Weeks

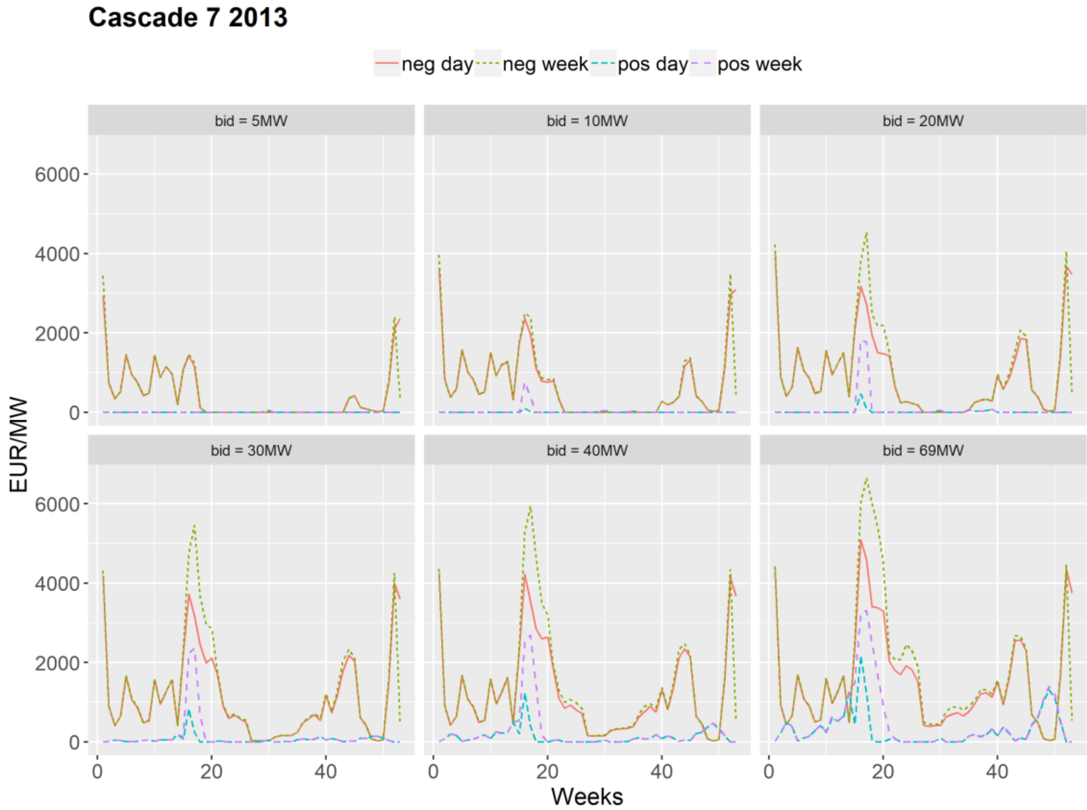


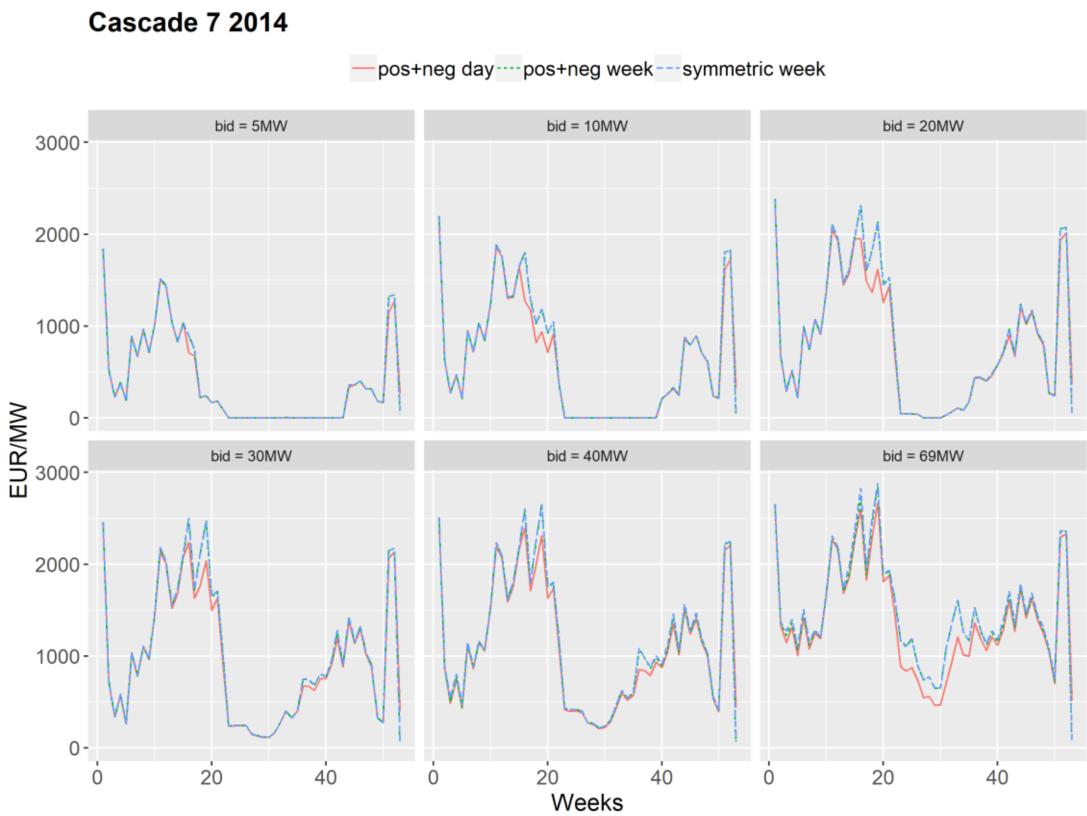
Cascade 6 2015
pos+neg day
pos+neg week
symmetric week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
EUR/MW
Weeks

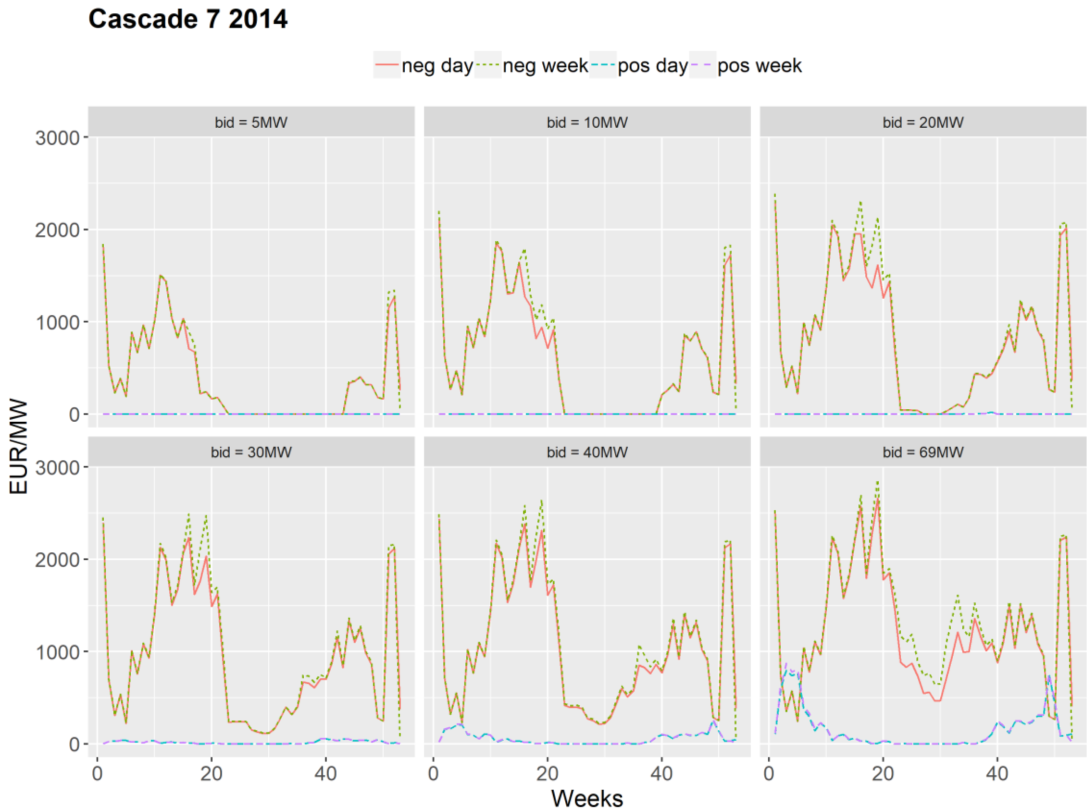


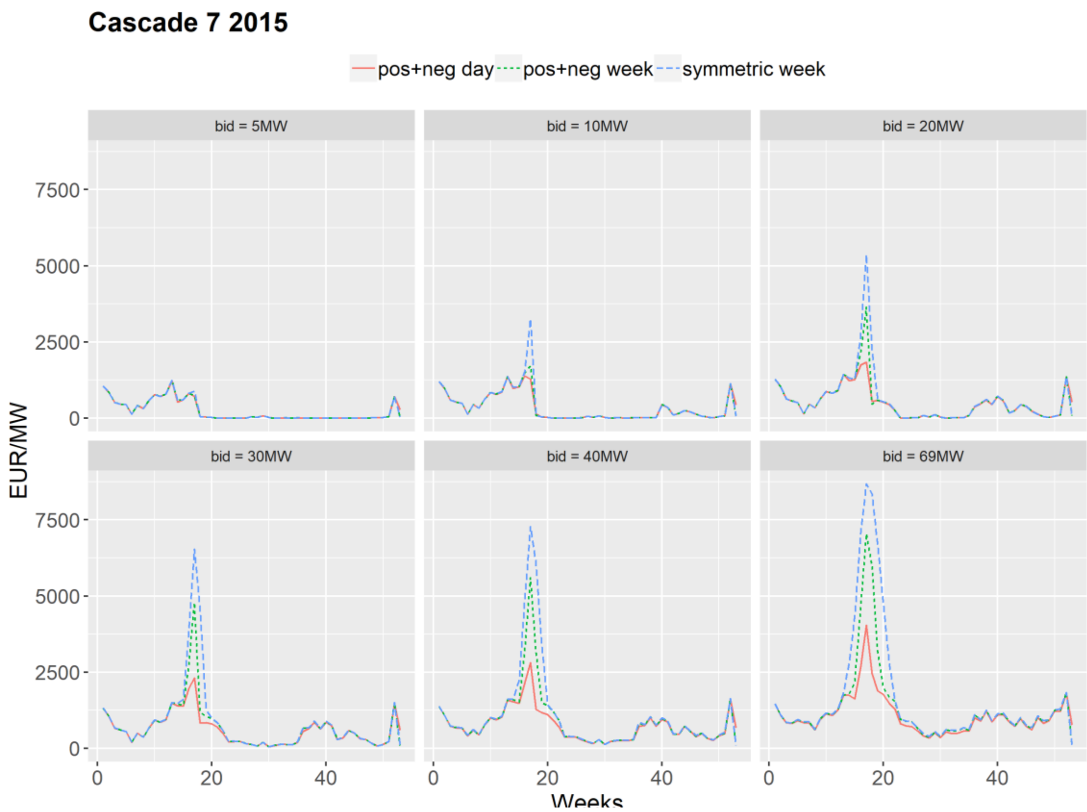
Cascade 6 2015
neg day
neg week
pos day
pos week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
EUR/MW
Weeks

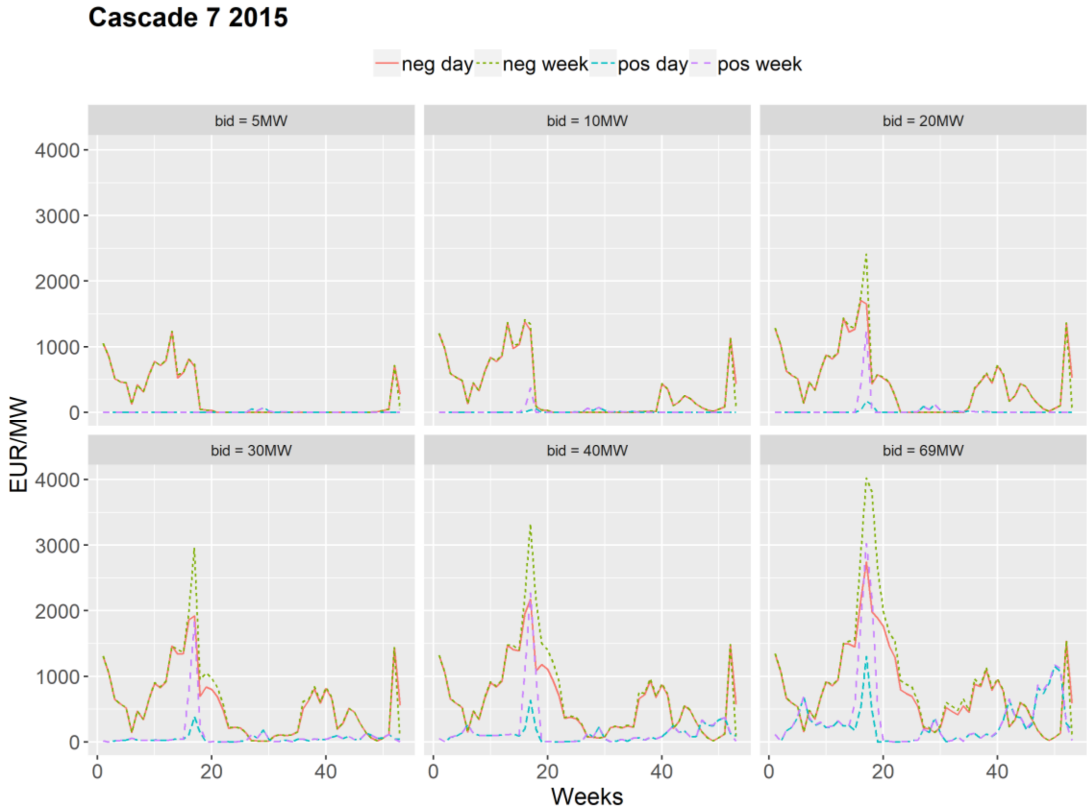

Cascade 7 2013
pos+neg day
pos+neg week
symmetric week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 69MW
EUR/MW
Weeks

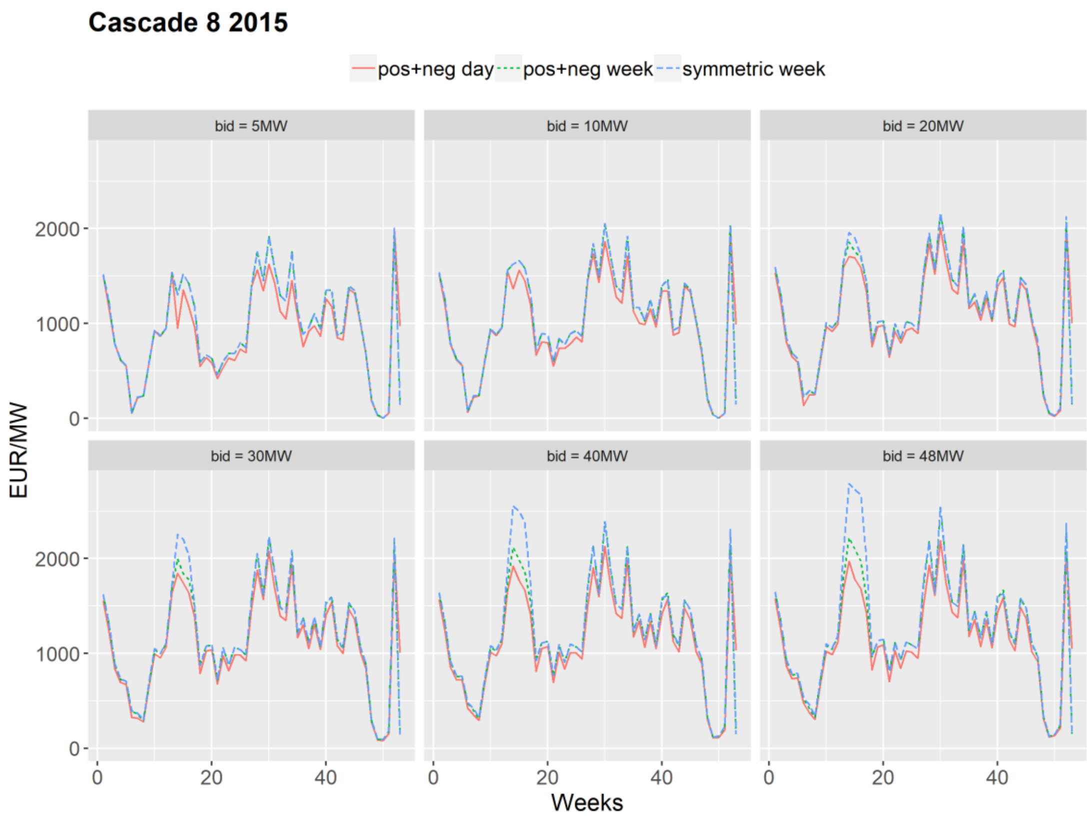

Cascade 7 2013
neg day
neg week
pos day
pos week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 69MW
EUR/MW
Weeks

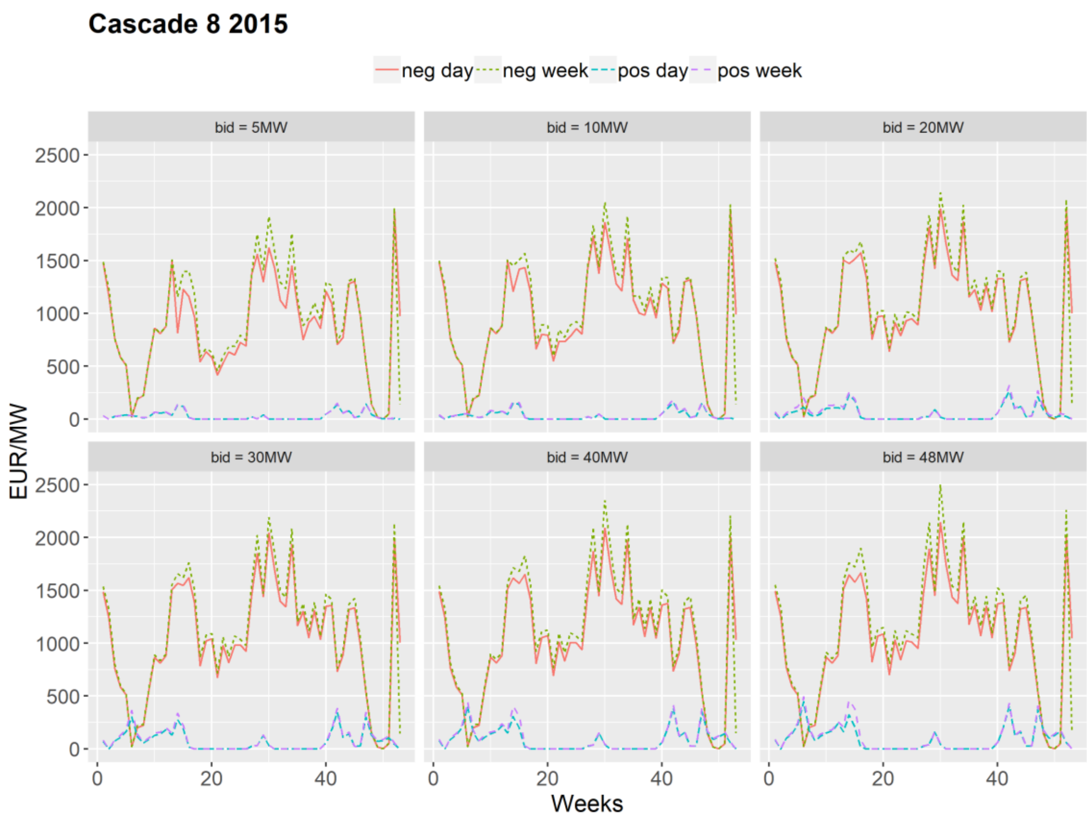

Cascade 7 2014
pos+neg day
pos+neg week
symmetric week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 69MW
EUR/MW
Weeks
0
1000
2000
3000
0
20
40


Cascade 7 2014
neg day
neg week
pos day
pos week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 69MW
EUR/MW
Weeks
0
1000
2000
3000
0
20
40


Cascade 7 2015
pos+neg day
pos+neg week
symmetric week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 69MW
EUR/MW
7500
5000
2500
0
20
40
Weeks

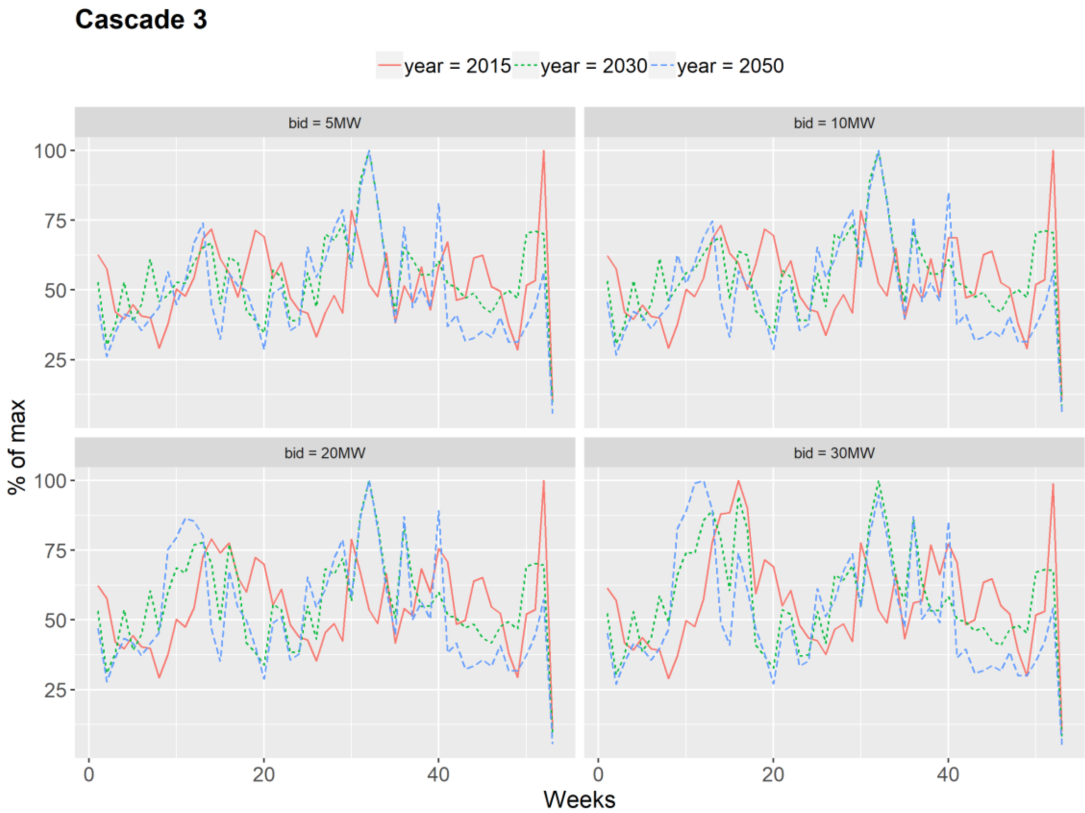

Cascade 7 2015
neg day
neg week
pos day
pos week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 69MW
EUR/MW
4000
3000
2000
1000
0
20
40
Weeks


Cascade 8 2015
pos+neg day
pos+neg week
symmetric week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 48MW
EUR/MW
Weeks
0
1000
2000
20
40

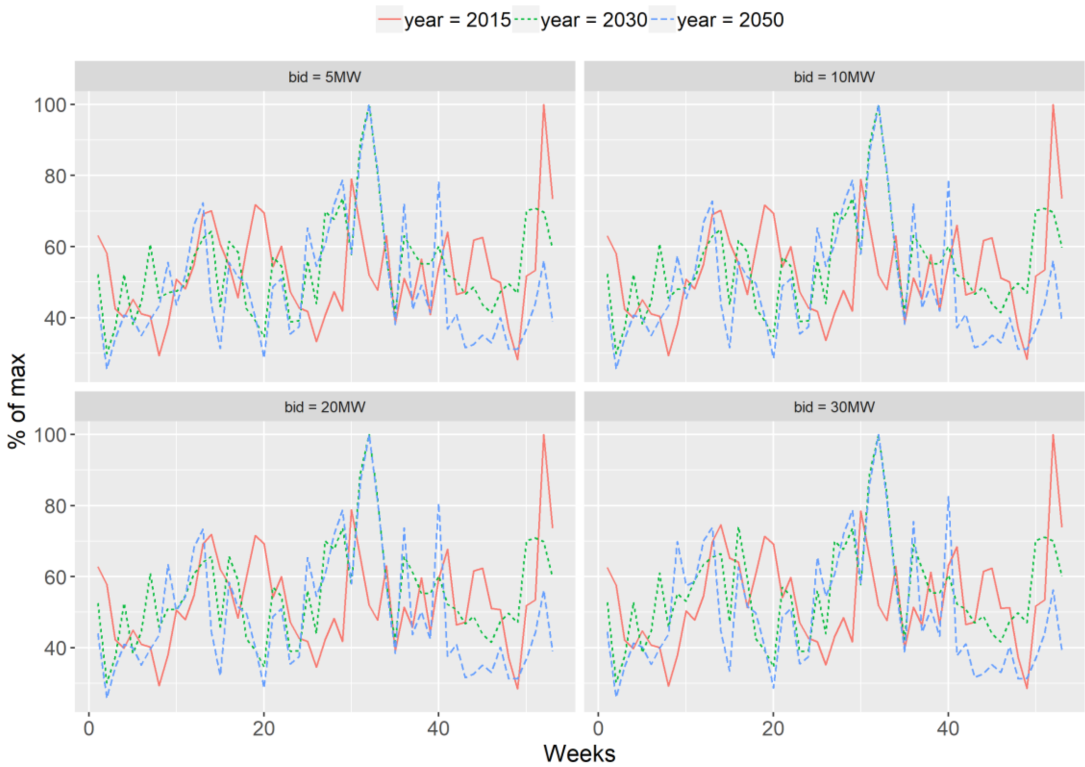

Cascade 8 2015
neg day
neg week
pos day
pos week
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 48MW
EUR/MW
Weeks
0
500
1000
1500
2000
2500
20
40

A2.5 Cost - Future

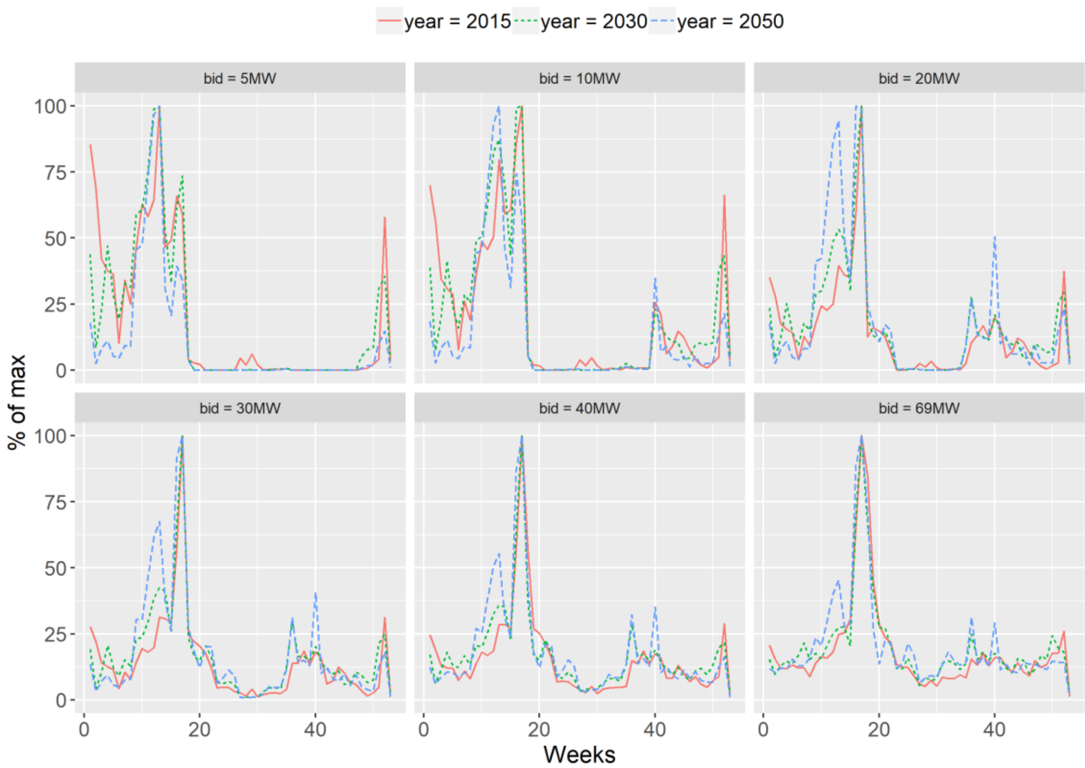
Figures A 14: Changes in opportunity cost dynamics by 2030 and 2050 for weekly (top figures for each cascade) and daily (bottom figures for each cascade) asymmetric SRL by cascade and bid size.



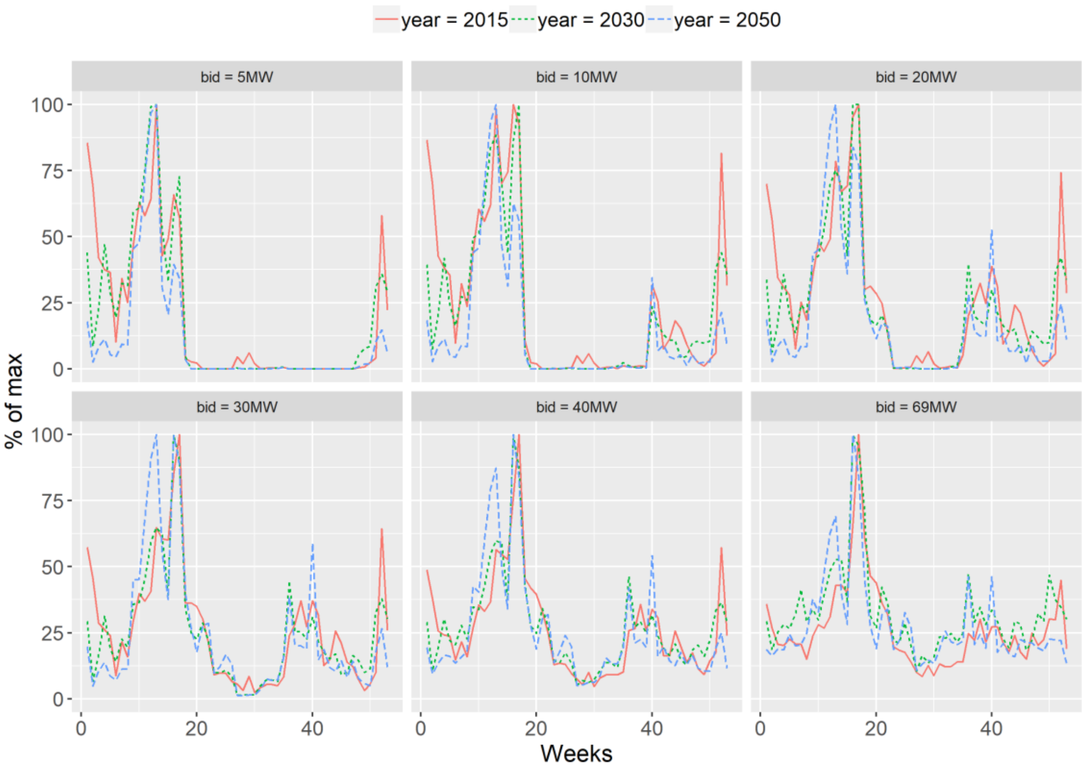
Cascade 3



Cascade 7



Cascade 7



year = 2015
year = 2030
year = 2050
bid = 5MW
bid = 10MW
bid = 20MW
bid = 30MW
bid = 40MW
bid = 69MW
% of max
100
75
50
25
0
0
20
40
Weeks