Chapter 9

A Techno-Economic Comparison of Demand Side Management with Other Flexibility Options

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Abstract This chapter assesses the techno-economic characteristics of demand side management (DSM) in comparison with other flexibility options (e.g., energy storages) in order to estimate its flexibility and benefit for the system integration of renewable energy sources (RES). The results show that load shedding and load shifting are less flexible than other flexibility options and can therefore only balance short-term fluctuations. In contrast, load increase is more flexible and can integrate excess feed-in from RES also over longer periods. Analysis about the impact of DSM on other flexibility options show, that DSM lowers utilization and contribution margin of peak load plants and energy storages, while it increases both for baseload power plants. More electricity is consumed nationally due to DSM as it decreases imports and exports.

9.1 Introduction

With increasing share of electricity generation from renewable energy sources (RES), the need for flexibility options, which balance intermittent feed-in from RES, rise as well. One balancing possibility is demand side management (DSM). The purpose of DSM is to smooth the (residual) load curve by reducing demand in peak times or increasing demand in off-peak periods. Another aim of DSM is to adapt electricity consumption to electricity generation (Gellings 1985; Behrangrad 2015; VDE 2012; ENTSOE 2017). DSM requires flexible consumers and applications, which can either curtail load during times of peak demand (load shedding), shift load to times of low demand, high RES feed-in (load shifting), or provide additional demand in times of excess feed-in from RES (load increase). Figure 9.1 presents exemplary applications and technologies for each of the three DSM categories.

The paper is based on own analyses which are published in more detail in the dissertation (Ladwig 2018).

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Fig. 9.1 Flexibility options categorized by type of flexibility provision (Source Figure adapted and based on Michaelis et al. [2017])

As load shedding applications reduce demand, they are (mainly) applied in times of positive residual load¹ (cf. Fig. 9.1). Thereby, they can reduce the need for electricity generation from thermal power plants. In contrast, load increase applications can balance negative residual load, as they use (mainly) excess electricity generation from RES to produce other energy carriers, e.g., hydrogen or heat. As a result, they can help to minimize or avoid curtailment of excess feed-in from RES. Load shedding applications can balance both, positive and negative residual load. Thus, they can fulfill the same tasks in an electricity system as energy storages and electricity grids.

These examples illustrate, that not only DSM can balance positive and/or negative residual load but also other flexibility options, e.g., thermal power plants or energy storages (cf. Fig. 9.1). DSM applications and flexibility options differ from each other regarding their technical and economic characteristics. Both characteristics determine the need and field of application of a flexibility option for the system integration of RES. Especially the flexibility of DSM is limited to avoid or minimize loss of comfort for the consumers. Therefore, the focus of the paper is to assess the techno-economic characteristics of demand side management in comparison with other flexibility options (e.g., energy storages) in order to estimate its flexibility and benefit for the system integration of RES. For this purpose, Sect. 9.2 presents the main technical and economics characteristics of DSM and compares them to other, competing flexibility options. Section 9.3 presents a model-based scenario analysis, where the trade-off between DSM and other flexibility options at the electricity

¹Residual load describes the difference between load and feed-in from RES. It is positive when demand is higher than RES feed-in and negative when demand is lower than RES feed-in.

market is investigated using the example of Germany. The paper closes in Sect. 9.4 with a conclusion, which summarizes the main findings.

The analysis was developed independently of the scenarios (Mod-RES and High-RES). The focus of this supplementary sensitivity is to analyse the potential and meaning of demand side management in an energy system with a high share of renewable energies.

9.2 Techno-Economic Characteristics of DSM in Comparison with Other Flexibility Options

9.2.1 Technical Characteristics of DSM

In order to avoid or minimize loss of comfort for the consumers or production losses in industry, the flexibility and thus the application of DSM are limited by technical restrictions. Main restrictions are:

- *Time of interfere* determines how long the demand of a DSM application can be reduced or increased.
- *Shifting time* needs to be considered for DSM applications of the category load shifting. It presents the maximum of minutes or hours, an electricity demand can be shifted to an earlier or later point in time.
- The *number of interventions* per day, week, month, or year is limited for almost all DSM applications, to minimize loss of comfort as well as production losses.

All three characteristics depend on the underlying process providing DSM. Thus, they can differ strongly between applications. For instance, ventilation and air conditioning systems can only shift their demand for about 1–2 h (as temperature levels have to be kept in a defined range), while heat pumps or electric vehicles show shifting times of about 12–24 h (as the necessary energy services are still guaranteed) (cf. Fig. 9.2). The shifting time strongly depends on the size of the connected storage. Figures 9.2 and 9.3 present the time of interfere and the shifting time for selected load shifting and load shedding applications. They are compared to an alternative and competing flexibility option, to assess their flexibility.

In general load shifting applications compete with energy storages as shifting electricity demand works similar to storing electricity. For instance, both increasing electricity demand as well as charging a storage aims (above others) to use cheap electricity, e.g., in times of excess generation from RES. Furthermore, reducing electricity demand corresponds to discharging a storage as both reduce the (residual) load. In order to investigate the fields of application for load shifting, it needs to be compared with energy storages. As benchmark, Fig. 9.2 presents the pump storage plant Goldisthal (PSP Goldisthal), which is a large and modern pump storage plant in Germany.

Fig. 9.2 Maximum time of interfere and shifting time of selected load shifting applications compared to the pump storage plant Goldisthal (*Source* Data according to Klobasa et al. [2013], Gils [2014] and own assumptions)

Fig. 9.3 Maximum time of interfere of selected load shedding applications compared to a representative gas turbine (*Source* Data according to Gils [2014] and own assumptions)

As described above, the time of interfere of some load shifting applications are small compared to others. E.g., air ventilation systems can only reduce or increase demand for up to two hours, while load shifting applications with larger storages, such as night storage heaters or electric vehicles, can change their consumption up to 12 h. The PSP Goldisthal can generate electricity for up to 8 h, when the upper storage reservoir is completely drained. Thus, its time of interfere lays in a same range as the one of load shifting applications with large-scale storages. However, the shifting time of PSP Goldisthal is much higher, as the one of load shifting applications. It can store water in its reservoirs over days or weeks (at least from a technical point of view). While load shifting applications have to balance decreased or increased demand within hours. Therefore, load shifting can mainly be used to balance short-term fluctuations of RES feed-in. If low wind periods or periods of excess generation from RES occur for longer time periods, it can only be balanced with large-scale energy storages, such as PSP.

Figure 9.3 illustrates three load shedding applications from industry (aluminum electrolysis, chlorine electrolysis, and electric arc furnace) in comparison with a

representative gas turbine. Both, load shedding applications and gas turbines, can be used for balancing load peaks. In case of load shedding applications, they reduce electricity demand in times with load peaks. Gas turbines produce electricity in these times. The time of interfere from industry processes is limited to four hours and the number of intervention is around 40 per year, to avoid (high) losses in production and profits. In contrast, the commitment of gas turbines is (from a technical point of view) only restricted by maintenance work. Therefore, it can produce electricity almost whenever it is needed. As a result, gas turbines are more flexible to balance load (peaks) as load shedding applications.

The presented two options (load shedding and load shifting) aim to decrease or shift demand. The third option in case of DSM is load increase, which consists of power-to-x technologies (PtX). PtX technologies play a major role in the HIGH-RES scenarios investigated in the REFLEX-project. These technologies increase electrification by shifting other energy demands to the electricity sector—so-called sector coupling—and thus contribute to a steeper growth of electricity demand. However, this requires a stronger extension of renewable energies in order to achieve the renewable energy as well as emission reduction targets.

PtX can be used, to consume excess electricity generation from RES. Alternatively, excess electricity generation from RES can be curtailed, when there is not enough infrastructure, e.g., energy storages or electricity grids, to integrate it into the electricity system. Several studies demonstrate, that it is from a system point of view not cost-optimal, to integrate even the last kWh electricity produced (cf. Müller et al. 2013). Therefore, it needs to be investigated, whether it is more cost-efficient to curtail excess electricity generation or to use PtX. With regard to technical restrictions, the time of interfere, and the number of interventions from PtX technologies, such as power-to-heat (PtH) or power-to-gas (PtG), is almost unlimited. It is only restricted with regard to the demand of the produced energy carrier, the plant size (e.g., electrolyzer or boiler) and the subsequent infrastructure, e.g., gas or heating grid. Thus, with regard to these parameters, it is more flexible than load shedding and load shifting. Furthermore, PtX benefits from a high time of interfere and high numbers of interventions. The higher the capacity utilization, the higher is the economic efficiency. In contrast, the longer excess generation from RES needs to be curtailed; the lower is the economic efficiency of the plant. Therefore, RES plants should operate as often as possible. From a technical point of view, their number of activations and time of interfere is only limited by their full load hours. Thus, they show no large differences compared to PtX technologies, with regard to the presented technical characteristics. In order to investigate, which of them leads to a more cost-efficient integration of RES, their costs needs to be analyzed.

The comparison of different DSM applications with competing flexibility options in this Sect. 9.2.1 demonstrate, that load shedding and load shifting applications can only be used to balance short-term fluctuations or load peaks which occur only for short-term periods. If they occur over longer periods, other flexibility options such as gas turbines or (pump storage) plants are needed. Furthermore, the use of these DSM applications is strongly limited by the number of interventions, to avoid loss of comforts for the consumers or loss of production in industry. In contrast, load

increase applications, such as PtG or PtH are more flexible than load shedding and load shifting applications. As a result, they can integrate excess electricity generation from RES also over longer periods. However, the commitment of DSM applications is determined by their costs. They are presented and compared to the ones of competing flexibility options in Sect. 9.2.2.

9.2.2 Activation and Initialization Costs of DSM

Costs for using DSM can be divided in two groups: activation and initialization costs. Initialization costs consist of investments and yearly fixed costs. These are mainly investments in infrastructure of measurement, control, and communication technologies. The operation of these technologies leads to yearly fixed costs, which needs to be considered in a cost assessment as well.

Activation costs occur immediately when the DSM potential is used, means as soon as the electricity demand increases or decreases. In case of load shedding applications in industry, they mainly consist of opportunity costs for profits lost. Activation costs of PtX are based on opportunity costs as well. They depend on the prices for the produced energy carriers. For instance, heat is only produced by an electric boiler (PtH), when its production cost is lower than the one of conventional methods (e.g., gas boilers). With regard to load shifting, activation costs represent costs for loss of comfort for the consumers or efficiency losses of underlying storages.

Activation and initialization costs depend on several exogenous factors, such as economic situation (e.g., sales potentials, prices for energy carriers); utilization of production or consumer behavior. Therefore, DSM costs are no fixed number but vary at any time. In addition, it is very difficult to quantify several cost parameters, e.g., comfort losses. Due to these reasons, Table 9.1 presents a range of activation and initialization costs. It shows on the one hand the monetary incentives, which consumers demand for changing their electricity consumption. On the other hand, it indicates the amount of investments to develop the potential. The numbers in Table 9.1 are derived from a system perspective. Therefore, activation costs can take positive and negative values. If it is positive, the consumer gets money for changing the electricity consumption. In case of load increase, additional electricity is consumed to generate heat or gas. It needs to be paid by the plant owner. Activation costs are therefore negative.

Activation costs mainly differ between the DSM categories load shedding, load shifting and load increase, while investment costs strongly vary between sectors. To develop the load shedding and load shifting potential, investments in infrastructure are needed. Most companies of the energy intensive industry in Germany have already an energy management system (Kohler et al. 2010). Therefore, the investments within the industry sector are low compared to the tertiary and residential sector, which show high investment costs due to a missing infrastructure for DSM. The investments for load increase represent costs for new power plants.

Table 9.1 Range of activation and initialization costs for selected DSM applications in Germany from a system perspective

		Activation costs	Initialization costs		
		[EUR/MWh]	Investments	Fixed costs	
			[EUR/kW]	[EUR/kWa]	
Load shedding	Chlorine electrolysis	30–310	1–20 ^a	0–1	Industry sector
	Electric arc furnace	130–1,000			
	Aluminum electrolysis	350–1,500			
Load shifting	Cement mill	0–6	40–1,200 ^a	25–90	Tertiary and residential sector
	Wood pulp production	0–10			
	Fridge and freezer	~ 0			
	Warm water heating	~ 0			
	Night storage heaters	~ 0			
	Air ventilation	~ 0			
	Air conditioner	~ 0			
	Heat pump	~ 0			
	Electric vehicles	~ 0			
Load increase	Power-to-gas	–(16.5–44.9) ^c	500–1,000 ^b	20–40 ^d	
	Power-to-heat	–(3.3–82.4) ^c	100–200 ^b	4–8 ^d	

^aInvestments for infrastructure, ^bInvestments in the system, ^cExcl. statutory dues, ^d4% of investments

Source Data according to Langrock et al. (2015), Kohler et al. (2010), Jentsch (2014), and Brunner et al. (2015)

DSM applications show large differences in case of activation costs due to the following reasons. Load shedding applications have the highest activation costs, as they are connected to production losses. The resulting loss of profit needs to be compensated. The profit losses are different for each process, as they depend on the price of the final product or the utilization of the process. Therefore, it is more cost-efficient to decrease the demand of a chlorine electrolyzer than of an aluminum electrolyzer. In case of load shifting, consumers benefit mainly from cost savings, when they consume electricity in times of lower electricity prices. The cost savings from DSM mainly depend on price volatility in the market. No compensation payments as those for load shifting applications are needed. Therefore, the activation costs from a

Fig. 9.4 Activation costs of DSM compared to a competing flexibility option (Source Data according to Ladwig [2018])

system perspective are nearly 0 EUR/MWh. In case of load increase, activation costs represent payments for electricity consumption. The values in Table 9.1 show the maximum electricity price which can be paid by PtX plant owners, to be competitive to conventional methods. The willingness to pay mainly depends on the sales price of the produced energy carrier.²

The activation and initialization costs of each DSM category are compared to competing flexibility options as presented in Figs. 9.4 and 9.5. The category conventional power plants consider gas, coal, and lignite power plants. Initialization costs include the annuity of investment and the yearly fixed costs. Variable costs of electricity generation represent the activation costs, which are fuel costs and costs for CO₂ allowances. The category RES curtailment considers wind onshore, wind offshore, and photovoltaic plants. Activation costs consist of their specific electricity generation costs, which plant owners demand in case of curtailment. Initialization costs consider investments in additional control devices and transaction costs. The category energy storage includes pump storage plants, compressed air energy storages, and lead-acid batteries. Their presented initialization costs consist of plant investments and yearly fixed costs.

Comparing conventional power plants and load shedding, the activation costs of power plants are significantly lower as the ones of load shedding. Consequently,

²Further information about the calculation of opportunity costs for PtX are presented in Ladwig (2018).

Fig. 9.5 Initialization costs of DSM compared to a competing flexibility option (Source Data according to Ladwig [2018])

balancing demand peaks with existing power plants is more efficient than using load shedding. With regard to initialization costs, the picture changes: they are significantly higher for power plants compared to load shedding. Therefore, the commitment of load shedding applications is only cost-efficient from a system perspective, when there is not enough generation capacity from power plants to fulfill the electricity demand. The comparison of RES curtailment and load increase shows similar results, as activation and initialization costs are also contrary. Due to the fact, that activation costs of load increase are negative, they are significantly lower as the ones for RES curtailment. With regard to initialization costs, RES curtailment is more cost-efficient than load increase. Based on the comparison of load shifting and energy storages, the activation and initialization costs fall in a similar range.

The comparison presented above, assesses separately activation and initialization costs. The results show, that either DSM or the competing flexibility option is preferable, depending on considering activation or initialization costs. Both cost components are relevant for a comprehensive assessment. In addition, full load hours need to be considered because the impact of initialization costs on total costs decrease with increasing operation time of a plant or application. Therefore, the following assessment focuses on total costs (including activation and initialization costs) as function of full load hours.

Figure 9.6 presents the total costs as function of full load hours for load shedding in comparison to conventional power plants. The commitment of load shedding is limited with regard to their technical restrictions to avoid (high) production

Fig. 9.6 Total costs of load shedding compared to conventional power plants as function of full load hours (Source Ladwig 2018)

losses. Based on the maximum number of activations and time of interfere, they have maximum full load hours of about 160 h per year. In case of low full load hours, the total costs of load shedding are smaller compared to power plants. Consequently, it is more cost-efficient to balance load peaks, which occur for only a few hours a year, with load shedding instead of building a new power plant. In all other cases, power plants are the preferable option.

The comparison of load increase and RES curtailment in Fig. 9.7 demonstrates, that the choice for one option depends on the utilization. From a system perspective it is more cost-efficient to curtail excess RES feed-in, which occurs only for a few hours a year, than building new PtX plants. When excess feed-in from RES occurs for several hours a year, it is more cost-efficient to build and use a new PtX plant, than RES curtailment.

In contrast to the shown comparisons, the total costs as function of full load hours of load shifting applications and energy storages are in a similar range (cf. Fig. 9.8).

Fig. 9.7 Total costs of load increase compared to RES curtailment as function of full load hours (Source Ladwig 2018)

Fig. 9.8 Total costs of load shifting compared to energy storages as function of full load hours (*Source* Data according to Ladwig [2018])

Thus, especially technical restrictions, e.g., availability and shifting time, influence the utilization and the fields of application for load shifting and energy storages.

The presented results are based on comparisons between DSM and competing flexibility options. However, in an electricity system DSM applications also compete with each other as well as with one of the other flexibility options. Especially load shifting applications compete with load shedding and load increase applications as well as with all other flexibility options as they can reduce load peaks and integrate excess RES feed-in. In order to assess the trade-offs and synergies between these options, further analysis with an energy system model is needed.

9.3 Impact of DSM on Other Flexibility Options

9.3.1 Framework of the Analysis

The previous results illustrate very well the technical and economic characteristics of DSM as well as its advantages and disadvantages compared to other flexibility options. However, it does not provide any insights about the trade-offs between DSM and other flexibility options at the electricity market. To investigate the impact of DSM on conventional power plants and energy storages as well as on imports and exports, an electricity market model is applied. The following assessment is performed with ELTRAMOD, which is a bottom-up electricity market model with a temporal resolution of 8,760 h. It calculates the cost-minimal generation dispatch, taking techno-economic characteristics of the generation facilities into account. The present analysis applies a model set-up that differs from the ELTRAMOD version, used in REFLEX. For more detailed information about the model, see Ladwig (2018), Müller and Möst (2018).

The analysis focuses on the German electricity market. But neighboring countries are modeled in an aggregated way as well, to adequately consider imports and exports. Electricity transmission between countries is calculated endogenously by ELTRAMOD. Figure 9.9 presents the model input regarding capacity of conventional

Fig. 9.9 Model input data regarding the capacity of RES and conventional power plants (Source Data according to Ladwig [2018])

Table 9.2 Considered DSM-options in the investigated scenarios

Scenario	Available DSM-options		
	Load shedding	Load shifting	Load increase
Excl. DSM	—	—	—
Incl. 2LS	x	x	—
Incl. DSM-all	x	x	x

Source Own illustration

power plants and RES plants. According to the targets of the German Government, a RES share of 80% is considered.

Three scenarios are investigated (cf. Table 9.2).³ The first one (*excl. DSM*) is the reference scenario, where no DSM-option is available. The other two differ with regard to load increase. Scenario *incl. 2LS* only considers load shedding and load shifting, while scenario *incl. DSM-all* considers all DSM categories (load shedding, load shifting, and load increase). To investigate the last two scenarios, the potential and the techno-economic characteristics of selected DSM applications are implemented in ELTRAMOD. Table 9.3 shows the respective input parameter with regard to the technical and economic parameter of DSM. Based on the calculations in Ladwig (2018) the following DSM potential was considered:

- Load shedding: 0.9 GW
- Load shifting: 83.9 TWh
- Load increase: 59.0 GW

³As mentioned before, these scenarios are independent from the three REFLEX scenarios (Mod-RES, High-RES centralized, and High-RES decentralized) and should be considered as an additional sensitivity analysis.

Table 9.3 Model input data related to DSM

		Time of interfere	Shifting time	Number of interventions	Activation costs
		[h]	[h]	[–]	[EUR/MW]
Load shedding	Aluminum electrolysis	4	–	40 per year	350
	Chlorine electrolysis	4	–	40 per year	130
	Electric arc furnace	4	–	40 per year	30
Load shifting	Wood pulp production	2	4	24 per year	0
	Cement mill	3	24	40 per year	0
	Fridge and freezer	1	1	<8 per year	0
	Warm water heating	12	12	–	0
	Air ventilation	1	1	<8 per year	0
	Air conditioning	1	1	<8 per year	0
	Heat pump	12	12	–	0
	Electric vehicle	<24	<24	–	0
Load increase	Power-to-gas	–	–	–	Depending on the price for natural gas
	Power-to-heat	–	–	–	

Source Data according to Gils (2014), Klobasa (2007), Langrock et al. (2015), and own assumptions

Further input data (e.g., technical characteristics of power plants, fuel prices, etc.) are presented in Ladwig (2018).

9.3.2 *Impact of DSM on the Operation of Conventional Power Plants and Pump Storage Plants*

At present, especially conventional power plants and PSP balance the intermittent feed-in of RES. For that reason, these plants cannot operate constantly but have to change operation mode depending on the residual load. DSM aims to smooth the residual load curve. As a result, load change activities of conventional power plants should decrease. To analyze this hypothesis, the standard deviation of the residual load and the number of load change activities are assessed. As presented in Table 9.4 the standard deviation of the residual load is about 35% lower, when DSM is applied compared to the scenario without DSM. Thus, DSM flattens the residual load curve.

Table 9.4 Standard deviation of residual load and average number of load change activities of power plants

	Excl. DSM	Incl. DSM-all	Difference
Standard deviation of the residual load (in GW)	26.9	17.4	−35%
Number of load change activities of power plants (incl. PSP)	51,412	30,303	−41%

Source Data according to own calculations

The number of load change activities of conventional power plants decrease as well. The numbers are about 41% lower in scenario incl. DSM compared to the scenario excl. DSM. Consequently, a reduced standard deviation of the residual load due to DSM results in less demand for load change activities of conventional plants.

In addition, smoothing the residual load curve with DSM affects the full load hours of conventional power plants. Figure 9.10 illustrates the change of full load hours, which results from DSM dispatch. It is the difference between the average full load hours per technology class from the scenarios excl. DSM and incl. DSM-all. For lignite, run-of-river and waste power plants the difference is positive, while it is negative for CHP plants and PSP. The utilization of reservoir power plants does not differ between the scenarios, as it runs at full capacity in both.

Figure 9.10 illustrates that using DSM results in higher full load hours for some technologies and minimizes the ones of others. This is due to the fact, that DSM increases demand in times with low or negative residual load and decreases it in times with high residual load (Ladwig 2018; cf. Chapters 6 and 7). Because of the demand increase in times with low or negative residual load, the number of hours with positive residual load raise as well. Base load power plants, such as lignite or run-of-river power plants, profit from this growth. They balance the additional demand, which results from this load increase. In contrast, DSM reduces demand in times with high residual load. Especially peak load plants, such as gas turbines and pump storage plants, operate in these times. As the number of hours and the

Fig. 9.10 Change of full load hours due to DSM (Source Data according to own calculations)

amount of load peaks decrease with DSM, the utilization of these plants decrease as well. Furthermore, energy storages, such as pump storage plants, profit from high load differences. They store energy in times of low residual load and discharge in times of high residual load. Due to DSM, these differences decrease as DSM reduces demand in times of high residual load and rise demand in times with low or negative residual load. Therefore, the operation of pump storage plants declines. Without DSM average full load hours of about 1,480 h occur, while with DSM the full load hours of pump storage plants are approx. 891 h. This example shows the direct competition between load shifting and energy storages. The round-trip efficiency of pump storage plants is typically about 75–80% (Schröder et al. 2013) due to losses for charging and discharging. The efficiency losses of load shifting are negligible. Therefore, it is from a system perspective more efficient to use load shifting than energy storages. But, the commitment of load shifting is much more restricted as the one of pump storage plants, due to its technical restrictions such as shifting time or number of activations. For that reason, load shifting can only balance short-term fluctuations of the residual load, while pump storage plants can store energy over days or weeks. Consequently, load shifting cannot replace energy storages completely but can reduce the demand of new storage plants.

DSM not only affects the residual load but also the electricity prices. Conventional power plants and storage plants receive revenues from electricity sales on the market. The price changes due to DSM affect the profitability of power plants and energy storages. To quantify this impact, the profit contribution margin of these technologies is assessed. It takes the sales revenues as well as the costs for CO₂ allowances, fuel and load changes into account. In order to compare the results, a specific contribution margin is calculated, which refers to the installed capacity. Figure 9.11 presents the results. It differs between the scenarios incl. 2LS (which considers only load shedding and load shifting) and incl. DSM-all (which considers additionally load increase) because the price level differs between both scenarios. The results from Ladwig

Fig. 9.11 Change of the specific contribution margin due to DSM (Source Data according to own calculations)

(2018) show, that load shedding and load shifting reduces the average electricity price, while load increase leads to a higher average price. As a result, the contribution margin of all technologies is lower in the scenario incl. 2LS compared to the scenario excl. DSM.

Reservoir and pump storage plants show the highest differences. Both technologies profit from high electricity prices in times of high residual load, which are reduced by load shedding and load shifting. This negatively affects the profitability of these plants. In addition, load shifting raises electricity prices in times with low or negative residual load. In this way, it makes electricity purchase for charging energy storages more expensive. Besides, the utilization of the plants decrease as presented above. The number of operation hours, when energy storage can earn money, decrease as well. Both effects (lower price differences and full load hours) reduce the contribution margin of pump storage power plants.

The scenario results for incl. DSM-all, where load shedding, load shifting, and load increase are considered, are illustrated in Fig. 9.11 as well. As mentioned before, load increase raises the electricity price in times with low residual load (cf. Ladwig 2018). Especially, lignite and run-of-river power plants profit from this price increase and their contribution margin rises (compared to the scenario excl. DSM). For all other technologies, the scenario results are similar to the scenario incl. 2LS. DSM leads to a lower contribution margin because of the lower prices in times with high residual load, which is caused by DSM.

The presented results show, that the impact of DSM on conventional power plants and energy storages differs: Baseload plants profit from higher demand and prices in times with low or negative residual load caused by DSM. While the utilization and contribution margin of peak load plants and energy storages decrease due to DSM.

9.3.3 *Impact of DSM on Imports and Exports*

In the following, the impact of DSM on imports and exports using the example of Germany is assessed. For this purpose, the commercial flows of the scenarios incl. DSM-all and incl. 2LS are compared to the scenario results excl. DSM. Figure 9.12 represents the differences, which result for each scenario.

Exports decline in both scenarios (compared to the scenario excl. DSM), while imports increase in scenarios with all DSM-options and decrease in the scenario without load increase. The differences between the scenarios incl. DSM-all and incl. 2LS result from load increase. PtX technologies raise demand in times with low or negative residual load. Therefore, less (excess) electricity is exported to neighboring countries. Furthermore, the additional demand of PtX technologies results in higher imports in some hours. Load shedding and load shifting reduce both, imports and exports, as they lower demand in peak times (when normally electricity is imported) and increase demand in times with low or negative residual load, which causes less exports. In addition, the results from Ladwig (2018) show that the amount of the

Fig. 9.12 Change of German imports and exports resulting from DSM (*Source* Data according to own calculations)

available DSM potential affects changes in imports and exports as well. The higher the DSM potential, the higher is the effect on the change in exports and imports.

To sum up, due to DSM more excess electricity from RES plants is nationally consumed. In that way, exports are reduced. In times with high residual load, DSM leads to fewer imports. Thereby, it reduces the dependency on electricity supply from neighboring countries in these hours.

9.4 Conclusions

With focus on the techno-economic characteristics from DSM applications, this paper investigates the flexibility of DSM and its interdependencies with other flexibility options, such as power plants and energy storages. DSM is categorized in load shedding, load shifting, and load increase. While load shedding and load shifting can balance mainly short-term fluctuations from demand and RES feed-in, load increase can integrate excess feed-in from RES which occurs over longer time periods.

All three DSM categories compete with other flexibility options. Therefore, the trade-offs to power plants and energy storages as well as to imports and exports are investigated. The results show, that baseload power plants, e.g., lignite power plants, profit from DSM. The reason is, that DSM increase demand and electricity prices in times of low residual load. Therefore, the utilization and the revenues of baseload power plants increase. In contrast, both components decrease for peak load plants, e.g., gas turbines, and pump storage plants due to the smoothing effect of DSM on the residual load and electricity price curve. Especially pump storage plants profit from high temporal differences in residual demand and electricity prices. DSM reduces both differences. Therefore, fewer situations occur, when PSP can charge or discharge their storages. For these reasons, DSM shows the highest impact on the utilization and profit contribution margin of PSP compared to other flexibility options.

In addition, the trade-off between DSM and imports/exports is investigated. Due to DSM, more electricity especially excess feed-in from RES is used nationally.

Therefore, exports decrease. In times with high residual load, imports decrease as well as DSM reduced load peaks. As a result, the national electricity supply is less dependent on electricity generation from neighboring countries in times of peak demand.

Considering all insights, the results show that the commitment of DSM applications is strongly limited by its techno-economic characteristics, e.g., shifting time or activation costs. DSM is in most cases less flexible than other flexibility options, e.g., gas turbines or energy storages. Therefore, a well-balanced mixture of DSM and other flexibility options is needed for an optimal system integration of renewable energy sources. With increasing electrification of demand side sectors or so-called sector coupling, future electricity demand rises, resulting in a growing need for flexibility provided by DSM.

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