Market4RES

D4.3 Quantification of the expected impacts coming from evolutions of RES support schemes and demand flexibility - Final report -

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EXECUTIVE SUMMARY

Introduction

The Work Package 4 (WP4) of the Market4RES project aims at quantifying the impacts of different market architecture options, assuming as an input the generation fleet expected for 2020[1]. The tool used to quantify the impacts of market architecture options is the OPTIMATE prototype simulation platform[2]. By using OPTIMATE, different market architecture options can be compared thanks to a set of selected indicators. This comparison is made by using different scenarios (installed capacities per energy source, level of peak demand, fuel prices, cross-border capacities, etc.) considered as input data, allowing for a sensitivity analysis of the impacts of the studied options with regards to different parameters, notably the level of RES penetration.

The purpose of the present report D4.3 is to present final results of the studies performed with the OPTIMATE tool within the WP4 of Market4RES. Two main studies have been performed, all based on specifications described in the Market4RES deliverable "Specifications of the most adequate options for flexibility markets and RES support schemes to be studied in a cross-border context" [1]:

- **Impact on short-term market outcomes of the foreseen evolution in RES support schemes (SS) from Feed-in-Tariffs (FiT) to Price Premium (PP):** the outcomes of this study have been reported into the Market4RES deliverable D4.2 "Quantification of the expected impacts coming from evolutions of RES support schemes and demand flexibility (intermediate report)" published in May 2015 [2];
- **Impact on short-term market outcomes of the development of demand flexibility:** the outcomes of this study are reported in the present deliverable D4.3[3].

Here, we consider as demand flexibility the load shedding voluntary done by consumers to arbitrate between high- and low-price hours. This supposes that consumers are exposed to hourly wholesale market prices. We do not discuss here the different possible market designs leading to such situation (incentives provided by electricity retailers, shedding directly controlled by the so-called "demand managers" or be left to consumers' decisions, provided that they are informed about the price of electricity, etc.). Still, whatever the possible market designs facilitating consumers' active participation in electricity markets are, demand response is nowadays perceived as a major flexibility source in the decades to come in order to successfully integrate high shares of RES electricity while controlling the overall cost of the power system. Quantifying the impacts of the large-scale deployment of demand flexibility is therefore needed: all stakeholders of the electricity

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[1] It therefore lies in the first Work Stream of the Market4RES project, while the second Work Stream focuses on post 2020 analyses. For more information see www.market4res.eu/.

[2] More information can be found on the OPTIMATE website www.optimate-platform.eu/.

[3] **Preliminary results of this study were also included in D4.2. However, the computation and the figures given in D4.2 about impacts of demand flexibility should be disregarded since updated in the present report.**

value chain (conventional and RES generators, consumers, network operators) are indeed likely to be impacted (in different ways) by such a change in consumption patterns.

Policy recommendations about demand flexibility deployment will be formulated in upcoming Market4RES reports under the work package 6 of the project "Conclusions, Recommendations & Procedure Guidelines". They will be based on the results of the present study and will also use the state of play of demand response in Europe, the barriers to its development and qualitative analyses developed in other work packages of the Market4RES project.

Scenarios underlying the studies

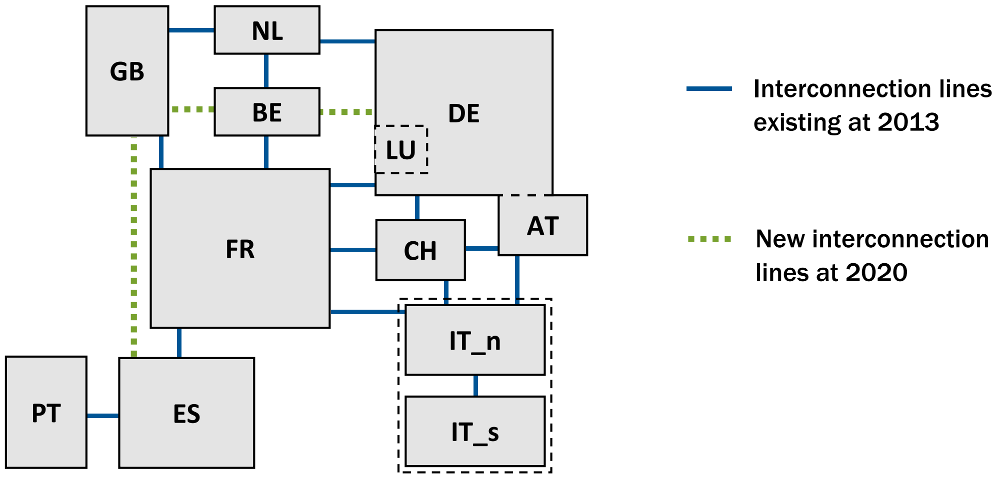
The studies are based on detailed specifications gathered in [1]. In particular, the above-mentioned market architecture options are studied and compared on the basis of different scenarios, in order to assess the sensitivity of the impacts of each option with regard to the main features of the power system (installed generation capacities, demand level, network capacities, etc.). Therefore, three scenarios are considered within the studies:

- The 2013 scenario, also called reference scenario, which mimics the current situation of the power system.
- The 2020 standard scenario which mimics the situation of the power system that can reasonably be expected at 2020. It is based on official publications such as the National Renewable Energy Action Plans (NREAPs) [3], ENTSO-E's Ten-Year Network Development Plan (TYNDP) 2014 [4], ENTSO-E's Scenario Outlook and Adequacy Forecast (SO&AF) 2014-2030 [5], etc.
- The alternative 2020 scenario RES+ is derived from the 2020 standard scenario. RES+ mimics a situation in which RES capacities replace some thermal capacities, the latter being both more flexible, and more costly through an increased CO_2 cost.

The studies are run over a geographical scope covering 11 countries as depicted here below[4].

[4] See D4.1 [1] for more details about this configuration.

Figure 1. *Geographical scope of the studies*



Configuration of the study about demand flexibility

The following hypotheses have been considered for the study about demand flexibility.

First, we consider **voluntary load shedding** as demand response to prices in the day-ahead market. For this, two variants have been adopted to model the deployment of demand flexibility:

- **Mid variant**: in this case, **5%** of the load is shed when prices reach the **95th centile** (in other words, during the 5% of the hours covered by the simulation with the highest prices);
- **High variant**: in this case, **10%** of the load is shed when prices reach the **90th centile** (in other words, during the 10% of the hours covered by the simulation with the highest prices).

In addition, demand shift can occur when load is shed: in principle, a certain proportion of the load which is shed during high-price hours should be shifted to low-price hours. This proportion being hardly assessable, it has been decided for the present study to consider two extreme situations:

- **No demand shift** (default option in OPTIMATE). This means that if peak load is shed, there is no compensation by an increase in electricity consumption during off-peak hours.
- **Full demand shift**: in this case, 100% of the peak load that is shed is compensated by an increase in consumption during off-peak hours possibly before and after the load shedding.

The impacts on the short-term market outcomes of these two extreme variants will therefore represent boundaries of the possible impacts of a realistic situation in terms of demand shift.

The combination between the different scenarios and demand flexibility variants is presented in the table below. In total, 15 cases are run with the OPTIMATE platform: for each scenario, four demand-flexibility variants are compared to one Default case[5].

Table 1. *Proposed combinations of scenarios and demand flexibility variants*

Studies	Scenarios	Demand flexibility	Demand shift
Default cases	2013	None	-
	2020 standard	None	-
	2020 RES+	None	-
Study on demand flexibility	2013	Mid	None
	2013	Mid	Full
	2013	High	None
	2013	High	Full
	2020 standard	Mid	None
	2020 standard	Mid	Full
	2020 standard	High	None
	2020 standard	High	Full
	2020 RES+	Mid	None
	2020 RES+	Mid	Full
	2020 RES+	High	None
	2020 RES+	High	Full

[5] Some parameters may have unexpected impacts on the study's results: it is therefore necessary to analyse different scenarios and different demand-flexibility variants in order to identify the main trends and isolate possible bias related for example to one specific scenario.

Main findings of the study about demand flexibility

The impact of the evolution of demand flexibility are assessed upon five families of indicators:

- Generation mix,
- Costs and profits,
- Market prices,
- Sustainability,
- Cross-border market integration.

Generation mix

- Demand flexibility has an impact mainly on the production coming from fossil fuels. Both production from gas and coal units decrease.
- In all countries, production from gas is significantly impacted by demand flexibility: this was expected since gas is one of the main peak generation means. Still, in countries with the highest amounts of generation from gas (Italy, Great Britain, Netherlands and Germany), the relative impact of demand flexibility is limited, since in those countries gas is not only used during peak hours but is actually a semi-base means.
- In countries with the highest coal generation (Germany, Great Britain, Italy and Spain), demand flexibility has little impact on coal production. It is in France and in Portugal that the deployment of demand flexibility impacts the most the generation from coal.
- If demand shift occurs, the production from gas units is less impacted compared to the production without demand shift. The same behaviour occurs for the coal production.
- The impacts of load flexibility and demand shift on the generation mix of each country is closely linked with cross-border flows.

Costs and profits

- Demand flexibility clearly impacts the thermal generation costs, since in general demand shedding will be applied when peak units are running (mainly based on fossil fuels). This impact increases with the development of demand response (from mid to high development) and with more RES penetration (from scenarios 2013 to 2020 standard and RES+).
- In terms of revenues, thermal producers are obviously impacted. First, as all other producers, their revenues are impacted by the decrease market prices due to load shedding. Second, the annual volume of energy generated by thermal power plants also decreases with demand flexibility: this is why the impact on thermal producers in terms of annual revenues is higher than those of RES producers (whose production remains stable).
- Still, the revenues of RES producers are also impacted by the price shaving due to demand flexibility. Wind and solar producers are impacted in different ways due to the different

production profiles combined with the load shedding profile, in particular for scenarios with high RES penetration.

- Finally, the consumer surplus also decreases with increasing deployment of demand flexibility. This is not an obvious impact since the deployment flexibility has logically two opposite impacts on consumer surplus: on the one hand, the decrease in market prices caused by load shedding should have a positive impact on the consumer surplus; on the other hand, the decrease in consumption should have a direct negative impact on consumer surplus. It appears that the latter impact is greater than the former.
- If demand shift applies:
    - Compared to demand flexibility without demand shift, the annual thermal generation costs decrease to a lower extent. This is consistent with what was expected, since the total production with demand shift is higher than without demand shift.
    - The annual thermal producer revenues follow the same trend, for the same reason: with demand shift, thermal generators produce more energy than without, thus earning higher revenues (volume effect). By contrast, in terms of average revenues per MWh generated for thermal producers, the trend is opposite: demand shift affects negatively their average revenue per MWh generated. This can be explained by the fact that demand shift is positioned during low price hours; therefore, with demand shift, thermal producers have to sell more energy during these low price hours than without demand shift; the impact on prices of demand shift is not high enough to compensate this effect.

Market prices

- Demand flexibility has a significant impact on average market prices: within all cases, this impact lies between -1% and -4%.
- In addition, there are significant differences between countries. For most of the countries studied, the impact of demand flexibility on the market price lies between -1% and -5%. Countries facing very high price peaks (within our modelling, Portugal is in this situation within the 2013 scenario) are much impacted since price peaks are significantly shaved.
- Demand flexibility has a major impact on the average daily spread (difference between the maximum price of the day within a given market area and the minimum price of the same day and market) with significant differences between the three scenarios and the market areas. Again, in countries facing high price peaks, the impact on the daily spread is most significant.
- Demand flexibility with demand shift, compared to demand flexibility without demand shift, has a slightly lower impact on the average market prices. This was expected since demand shift increases the prices during low-price hours. For the very same reason, demand shift allows decreasing even more the average daily spread, leading to a very significant impact.

Thanks to load shedding combined with demand shift, on average, the residual load[6] is flatter, and so are the average prices.

Sustainability

- Demand flexibility has an important impact on CO_2 emissions compared to the proportion of load shed. Within our hypotheses, between 10 and 39 million of tons (Mt) of CO_2 would be saved each year, representing 0.7% to 3.7% of the total CO_2 emissions from power generation. The distribution per country of these savings depends on the impacts on fossil fuel generation which has been previously described.
- The existence of demand shift would allow lower savings, from 5 to 29 Mt depending on the different scenarios cases studied.

Cross-border market integration

- Demand flexibility causes a general increase of cross-border flows, and the interconnection utilization rate increases. This means that cross-border interconnections are used closer to their full capacity (in the relevant market direction).
- The average price differential magnitude drops, in particular within the 2013 scenario. This is related to the previous point, but also to the decrease in the average prices within each market as previously described: price peaks being shaved, price differentials between countries are also reduced, on average.
- Still, the occurrence of price convergence significantly decreases. This means that even if on average, prices are closer to each other, they are less often equal. This is in fact consistent with the increase of the interconnection utilisation rate: when interconnections are fully used, it means that prices are not necessarily equalized.
- The congestion revenue depends on the amount on cross-border flows, and on the price differentials. The increase in cross-border flows being low compared to the decrease in average price differential, the impact of demand flexibility on congestion revenue is negative. Within our estimates, the decrease in the total congestion revenue would lie between 0.2% and 6.8% depending on the cases and the scenarios.
- On individual borders, the impacts of load shedding possibly combined with demand shift vary a lot. On borders with a very high use of interconnection capacities always in the same direction, the changes in market prices on each side of the borders caused by demand flexibility are not high enough to change the general patterns of the flows.
- In countries with high interconnection capacities, load shedding and demand shifts are partially compensated by domestic production, the rest being addressed by an adaption of cross-border flows. By contrast, within "electric peninsulas" (with lower import/export

[6] **The residual load is the difference between load and non-dispatchable generation such as wind, solar and must-run.**

capacities) load shedding and demand shifts must be compensated mainly with an adaptation of the domestic production.

Conclusion

In order to achieve European Union energy policy and decarbonisation targets, demand flexibility can be a key component. Quantifying the benefits of demand flexibility is however very challenging and complex, since the needs and the interconnection of energy systems are very heterogeneous throughout Europe. Indeed, consumers' habits and density, level of industrialization, generation mix and geographic structure are all factors that make this assessment complex.

Furthermore, demand response can be related to either shifting electricity demand from periods of high prices to periods of lower prices, or to reducing electricity consumption in periods of high prices (with no consumption shifting). In the present study, it has been decided to consider two extreme situations: on the one hand, no demand shift is associated to load shedding; on the other hand, full demand shift occurs (meaning that no global energy savings occur). These two extreme variants represent boundaries of the possible impacts of a realistic situation in terms of demand response behaviour. In further studies, it could be possible to model a mixed situation (for example 50% of demand shift); it could also be possible to combine demand flexibility development with other market design aspects such as renewable support schemes. Still, carrying out such studies being very complex, not all possibilities could have be included in the work performed within the framework of the Market4RES project. Also, studying the impacts of demand response on a restricted geographical scope but including the modelling of local network constraints and of shorter-term markets (intraday, balancing) could be the purpose of future studies to be done with the OPTIMATE tool.

The present report outlines many impacts of demand flexibility. It is now legitimate to ask what the policy recommendations following these studies can be. Elements to answer this fundamental question will be addressed in upcoming Market4RES reports under the work package 6 of the project "Conclusions, Recommendations & Procedure Guidelines".

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1 INTRODUCTION

1.1 Role of WP4 in the Market4RES project

The Work Package 4 (WP4) of the Market4RES project aims at quantifying the impacts of different market architecture options, assuming as an input the generation fleet expected for 2020. [7]

The tool used to quantify the impacts of market architecture options is the OPTIMATE prototype simulation platform. This prototype tool was developed during an FP7 project[8], which aimed at developing a numerical test platform to analyse and to validate new market designs, which may allow integrating massive flexible generation dispersed in several regional power markets[9].

By using OPTIMATE, different market architecture options can be compared thanks to a set of selected indicators. This comparison is made by using different scenarios (installed capacities per energy source, level of peak demand, fuel prices, cross-border capacities, etc.) considered as input data, allowing for a sensitivity analysis of the impacts of the studied options with regards to different parameters, notably the level of RES penetration.

1.2 Purpose of this report

The purpose of the present report D4.3 is to present final results of the studies performed with the OPTIMATE tool within the WP4 of Market4RES. Two main studies have been performed, all based on specifications described in [1]:

- **Impact on short-term market outcomes of the foreseen evolution in RES support schemes (SS) from Feed-in-Tariffs (FiT) to Price Premium (PP):** the outcomes of this study have been reported into the deliverable D4.2 " Quantification of the expected impacts coming from evolutions of RES support schemes and demand flexibility (intermediate report)" published in May 2015 [2];
- **Impact on short-term market outcomes of the development of demand flexibility:** the outcomes of this study are reported in the present deliverable D4.3.[10]

Demand response consists in reducing or increasing the load level of consumers for some time when the price of electricity reaches a high/low enough level. Here, we consider only the voluntary load shedding done by consumers to arbitrate between high- and low-price hours. This supposes that consumers are exposed to hourly wholesale market prices. We do not discuss here the different possible market designs leading to such situation. This reduction/activation can indeed

[7] It therefore lies in the first Work Stream of the Market4RES project, while the second Work Stream focuses on post 2020 analyses. For more information see www.market4res.eu/.

[8] Grant Agreement 239456.

[9] More information can be found on the OPTIMATE website http://optimate-platform.eu/.

[10] **Preliminary results of this study were also included in D4.2 [2]. However, the computation and the figures given in D4.2 about impacts of demand flexibility should be disregarded since these have been updated in the present report.**

either be directly controlled by the so-called "demand managers" or be left to consumers' decisions, provided that they are informed about and exposed to the actual price of electricity. Still, whatever the possible market designs facilitating consumers' active participation in electricity markets are, demand response is nowadays perceived as a major flexibility source in the decades to come in order to successfully integrate high shares of RES electricity while controlling the overall cost of the power system. Quantifying the impacts of the large-scale deployment of demand flexibility is therefore needed: all stakeholders of the electricity value chain (conventional and RES generators, consumers, network operators) are indeed likely to be impacted (in different ways) by such a change in consumption patterns.

Moreover, demand response can be related to either shifting electricity demand from periods of peak demand, and typically high prices, to periods of low demand and typically lower prices, or to reducing electricity consumption in periods of peak demand (with no consumption shifting). Typical cases of consumption shifting would be the development of demand response for electric vehicles and for thermal usages. In those cases, demand-response would allow shifting the consumption halted by load-shedding to off-peak hours, but would lead to few or none overall energy savings. Typical cases with no consumption shifting would be the development of demand response for lightning usages (public lightning, decorative façade lightning). In those cases, demand-response would not only allow the consumption peak shaving, but would also result in higher overall energy savings.

The impacts of demand response are therefore very complex to analyse, since they highly depend on hypotheses considered regarding the behaviour of demand (with or without consumption shifting associated to load shedding). They also depend on other hypotheses like the renewable penetration, the flexibility of generation, the level of interconnection capacity, etc.

Impacts of demand response have already been analysed: several studies can be found in the literature (see references [6] to [13]). The purpose of the present study is to propose a complementary approach based on the OPTIMATE tool, which allows measuring possible impacts on short-term market outcomes of the development of demand flexibility. Within this report, assumptions, scenarios and modelling limitations are transparently presented.

In the OPTIMATE simulator, as a default option, most of the demand is considered inelastic, i.e. voluntary load shedding is not possible. However, demand can be set to have a flexible part (relative to the overall schedule), which can be voluntarily shed when price signals are adequate. Hence, the goal of this study is to assess *how demand flexibility would impact the day-ahead market outcomes.*

Policy recommendations about demand flexibility deployment will be formulated in upcoming Market4RES reports under the work package 6 of the project "Conclusions, Recommendations & Procedure Guidelines". They will be based on the results of the present study and will also use the state of play of demand response in Europe, the barriers to its development and qualitative analyses developed in other work packages of the Market4RES project.

1.3 Structure of this report

This report is structured as follows.

Chapter 2 provides the general framework for the analyses. The methodology used to quantify and compare the impacts of different market architecture options with OPTIMATE is briefly presented, and the limitations of the chosen modelling are reminded. The main features of the three scenarios supporting the study are described, and the geographical and temporal scope of the study is set.

Chapter 3 presents the configuration of demand flexibility. First, the general principles for configuring demand flexibility are explained. Afterwards, the modelling of demand shift from high-price hours to low-price hours is explained. It is illustrated with some typical examples.

Chapter 4 gathers the outcomes of the analyses performed with OPTIMATE. It is structured along five families of indicators: generation mix, costs and profits, market prices, sustainability, and cross-border market integration. First, the cases WITHOUT demand shift are studied; afterwards, cases WITH demand shift are analysed and compared with the findings WITHOUT demand shift.

2 FRAMEWORK FOR THE ANALYSES

2.1 Overview of the methodology used to quantify and compare the impacts of different market architecture options with OPTIMATE

OPTIMATE is a numerical simulation platform[11] designed to compare wholesale short-term electricity market architecture options integrating massive intermittent electricity generation in Europe, complying with the three EU energy pillars (economic efficiency, climate policy and security of supply). The OPTIMATE prototype platform was developed during an EC-funded FP7 project (2009-2012[12]) under the technical direction of RTE.

The OPTIMATE simulator has been designed rather to give trends in order to ease discussions among electricity stakeholders on system and market design updates, than to lead to absolute results. Consequently, variational studies are conducted: a reference set of designs is used for the comparison of results based on selected indicators.

In a nutshell, the methodology to compare market architecture options is the sequence of four elements: INPUTS, CORE, OUTPUTS and SCOPE (see Figure *2* below):

1. INPUTS: First of all, **scenarios** are generated. A scenario gathers a set of coherent data describing the initial state of the European power system and is consistent with a reference equilibrium of the market. Then, a range of **market architecture options** is set.
2. CORE: The OPTIMATE core then simulates the sequence of actions conducted by market players. It is made of four main processes: Day-Ahead, Intra-Day, Real-Time (including imbalance settlements) and the (feedback) learning-by-doing loop. Each process is made of modules simulating a specific task.[13]
3. OUTPUTS: Once the core simulation is over, outputs are delivered and studied using standard quantified indicators relying on the three pillars of the EU energy policy.
4. SCOPE: Finally the scope of the analysis is taken into account, namely the impacts of the OPTIMATE modelling assumptions on the results as well as other qualitative issues not measured by the OPTIMATE simulator.

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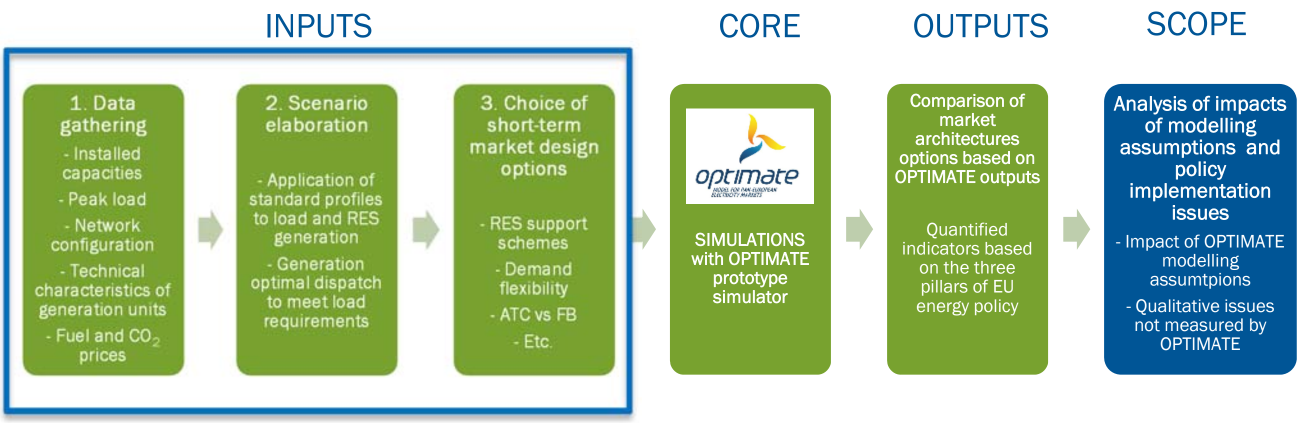
[11] See http://www.optimate-platform.eu/.

[12] "An Open Platform to Test Integration in new Market designs of massive intermittent Energy sources dispersed in several regional power markets" (contract no:239456).

[13] **In the present studies, only modules linked to the day-ahead markets are used, because the other modules were not fully operational when the Market4RES studies were launched in 2014.**

Figure 2. *Methodology to compare electricity market architectures*



The report D4.1 “Specifications of the most adequate options for flexibility markets and RES support schemes to be studied in a cross-border context” [1] was focused on the first step of this methodology (INPUTS) and its related tasks, and also provided insights about the indicators to be studied for each set of scenarios and market architecture options.

The present deliverable D4.3, as well as the previous deliverable D4.2 “Quantification of the expected impacts coming from evolutions of RES support schemes and demand flexibility (intermediate report)” [2], are focused on the third step of the methodology (OUTPUTS).

The main modelling assumptions and limitations of the OPTIMATE prototype used in these studies are detailed in D4.1 and D4.2, and are not repeated here. Two important considerations should however be reminded:

- **Only modules linked to the day-ahead markets are used within this study.** Therefore, the impacts of demand flexibility deployment are measured only on the day-ahead market. Benefits of demand-side participation in shorter term markets (intraday, balancing) are not considered within the present study.
- **Network constraints internal to market zones are not considered in the modelling.** Therefore, some problems that can arise in real-life and that could be (partly) solved by demand flexibility (regarding for example difficulties in evacuating RES production at local level, possibly leading to RES curtailment) are not modelled within this study. Therefore, the potential benefits of demand response with regards to local problems are not measured: only the benefits at global scale are taken into account in the present study.

2.2 Elaboration of scenarios to compare market architecture options

Different demand flexibility options are studied and compared on the basis of different scenarios, in order to assess the sensitivity of the impacts of each option with regards to the main features of the power system (installed generation capacities, demand level, network capacities, etc.). Therefore, each simulation run consists in combining a scenario and a demand flexibility option (as presented in *Table 3*, page 24).

Table 2 below presents the main features of the scenarios being elaborated for the studies in a synthetic and qualitative manner. The detailed description of each scenario can be found in D4.1 "Specifications of the most adequate options for flexibility markets and RES support schemes to be studied in a cross-border context" [1].

- The 2013 scenario, also called reference scenario, mimics the current situation of the power system.
- The 2020 standard scenario mimics the situation of the power system which can reasonably be expected at 2020. It is based on official publications such as the National Renewable Energy Action Plans (NREAPs) [3], ENTSO-E's Ten-Year Network Development Plan (TYNDP) 2014 [4], ENTSO-E's Scenario Outlook and Adequacy Forecast (SO&AF) 2014-2030 [5], etc.
- The alternative 2020 scenario RES+ is derived from the above-mentioned 2020 standard scenario. RES+ mimics a situation in which RES capacities replace some thermal capacities, the latter being both more flexible and more costly.

Table 2. *Main features of each scenario*

Scenario name	Thermal generation			RES generation	Demand	Transmission network
	Installed capacities	*Flexibility*	*Economic parameters*			
2013 scenario (reference scenario)	Current installed capacities	Current flexibility level	Current CO_2 price and fuel costs	Current installed capacities	Current level of peak demand	Current cross-border capacities
2020 standard scenario	Installed capacities at 2020 as foreseen today	Current flexibility level	Foreseen values at 2020	2020 RES objectives	Level of peak demand at 2020 as foreseen today	2020 cross-border capacities as foreseen today
2020 RES+ scenario	Significant decrease in thermal installed capacities	Higher flexibility of thermal units	Higher CO_2 price (impact on merit order curve)	Additional RES capacities	Level of peak demand at 2020 as foreseen today	2020 cross-border capacities as foreseen today

2.3 Evaluation of market architecture options by comparison with a Default case

For each scenario, a Default case has to be chosen: the impacts of market architecture options are assessed by comparison with this Default case. In the present study, the Default case consists in applying no demand flexibility (voluntary load shedding is not possible).

The impacts of market architecture options compared to the Default cases are measured along five families of indicators (as described in D4.1 [1] and D4.2 [2]):

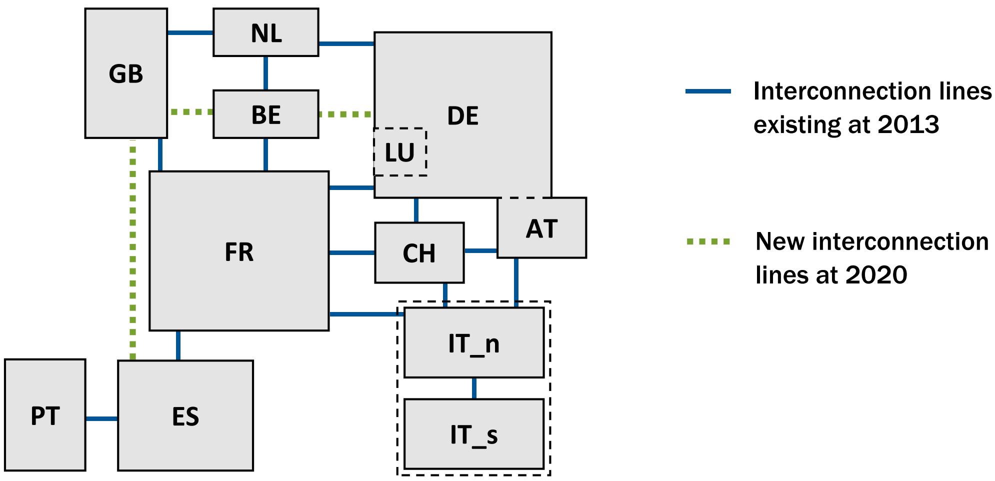
- Generation mix,
- Costs and profits,
- Market prices,
- Sustainability,
- Cross-border market integration.

2.4 Geographical and temporal scope of the study

2.4.1 Geographical scope of the study

All scenarios are built upon the same geographical scope covering **11 countries** as depicted in ***Figure 3*** below[14].

Figure 3. *Geographical scope of the studies*



2.4.2 Temporal scope of the study

Initially, to grasp the potential seasonal effects of the different market architecture options, while limiting the computation time of the OPTIMATE simulator, each case was foreseen to be run over 6 months, from February to July (thus covering 3 different seasons). With the version of the prototype tool initially used within Market4RES (v.10), the computation time for running one case over 6 months was about 10 days. It was therefore not doable to run the cases over one full year.

Eventually, the v1.11 release of the OPTIMATE prototype has greatly decreased the computation time by dividing it by 9, making it feasible to launch studies covering 12 months. Therefore,

[14] See D4.1 for details about this configuration.

contrarily to what has been done for D4.2, the temporal scope of the study about demand flexibility is **one full year.**

3 CONFIGURATION OF DEMAND FLEXIBILITY

3.1 General principles

Within this study, demand flexibility is configured along three dimensions.

First, the **level of controllable load**, expressed as a percentage of peak load, corresponds to the proportion of appliances that can be switched off or have their intensity decreased.

Second, the **price above which load shedding is triggered** needs to be set. In other words, demand flexibility is modelled as voluntary load shedding responding to day-ahead market prices.

In the present study, these first two dimensions are translated into two variants of demand flexibility:

- **Mid**: in this case, **5%** of the load is shed when prices reach the **95th centile** (in other words, during the 5% of the hours covered by the simulation with the highest prices);
- **High**: in this case, **10%** of the load is shed when prices reach the **90th centile** (in other words, during the 10% of the hours covered by the simulation with the highest prices).

Third, **demand shift** can occur when load is shed. For example, if heating devices are shed during one hour, then during the next hours their consumption should increase in order to maintain the indoor temperature close enough to the set point. Also, for some appliances, load shedding can be anticipated, and shifts can be made during the hours before (for instance, for washing-machines). By contrast, for some appliances like lighting, switching them off at a certain hour does not imply shifts at any other hour.

Defining the average features of such demand shift, corresponding to residential and industrial load in the different countries within our scope, would be very challenging. We have not found any commonly accepted useful assessment of the way to model shifts in the available literature. Therefore, it has been decided for the present study to consider two extreme situations:

- **No demand shift**: (default option in OPTIMATE). This means that if peak load is shed, there is no compensation by an increase in electricity consumption during off-peak hours.
- **Full demand shift (FDS)**: in this case, 100% of the peak load that is shed is compensated by an increase in consumption during off-peak hours possibly before and after the load shedding.

The impacts on the day-ahead market outcomes of these two extreme variants will therefore represent the boundaries of a realistic situation in terms of demand shift.

The latter variant is not implemented in the current OPTIMATE prototype. Therefore, a methodology to model demand shift has been developed for the purpose of Market4RES, as described in section 3.2 below.

Table 3 presents in a synthetic manner how the different scenarios and demand flexibility variants are combined. In total, 15 cases are run with the OPTIMATE platform: for each scenario, four demand-flexibility variants are compared to one Default case. Some parameters may have unexpected impacts on the study's results: it is therefore necessary to analyse different scenarios and different demand-flexibility variants in order to identify the main trends and isolate possible bias related for example to one specific scenario.

Table 3. *Proposed combinations of scenarios and demand flexibility variants*

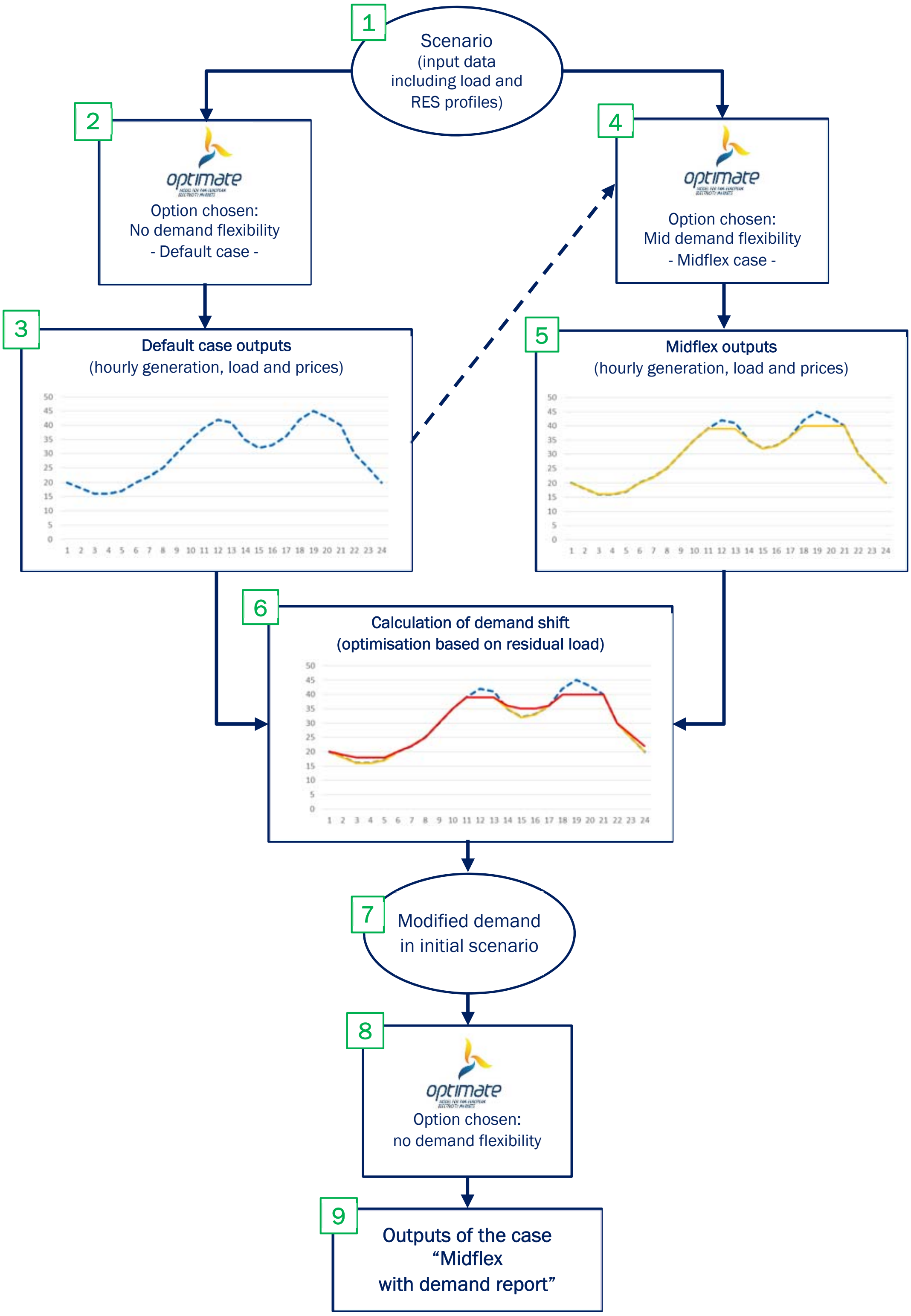
Studies	Scenarios	Demand flexibility	Demand shift
Default cases	2013	None	-
	2020 standard	None	-
	2020 RES+	None	-
Study on demand flexibility	2013	Mid	None
	2013	Mid	Full
	2013	High	None
	2013	High	Full
	2020 standard	Mid	None
	2020 standard	Mid	Full
	2020 standard	High	None
	2020 standard	High	Full
	2020 RES+	Mid	None
	2020 RES+	Mid	Full
	2020 RES+	High	None
	2020 RES+	High	Full

3.2 Modelling of demand shift from high-price hours to low-price hours

3.2.1 Methodology

The methodology implemented to model demand shifts caused by load shedding is graphically represented in *Figure 4* below.

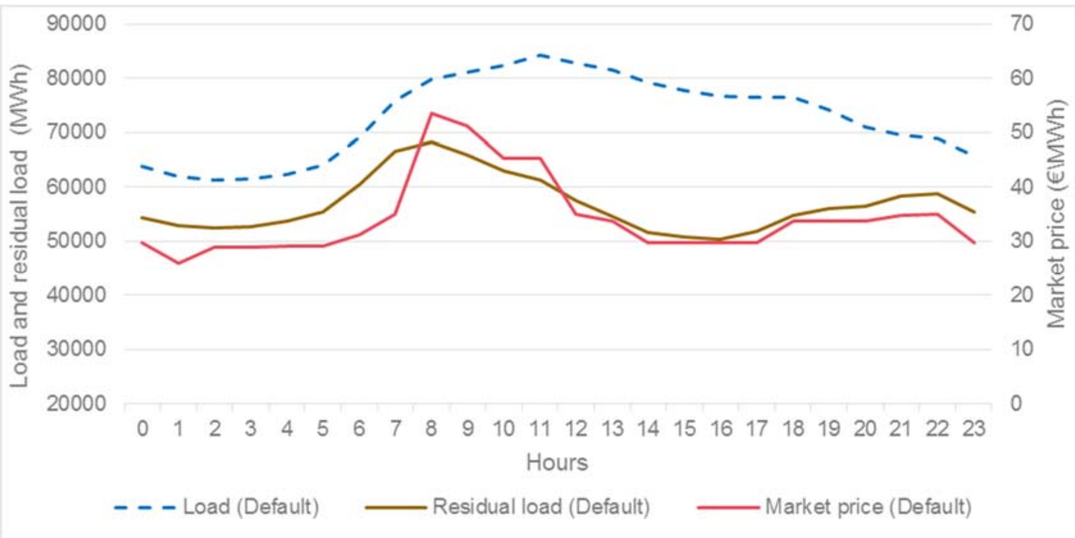
Figure 4. *Methodology to model demand shifts caused by load shedding (MidFlex case)*



It is a multistep approach, consisting in:

- Based on the input data corresponding to a given scenario (step 1), the Default case is run (step 2). Its outputs are, amongst other indicators, the day-ahead clearing quantities for load and generation, and the corresponding hourly prices (step 3).
- Then, the case with demand flexibility is run (step 4). On ***Figure 4***, the "MidFlex" case is mentioned, but actually the same applies for the "HighFlex" case. In both cases, load shedding occur, when prices reach a certain level calculated by using the price distribution of the Default case: this is the meaning of the dotted line from (3) to (4) in the figure. For the MidFlex case, 5% of the load is shed when prices in the Default case reach the 95th centile; for the HighFlex case, 10% of the load is shed when prices in the Default case reach the 90th centile.
- The outputs of the MidFlex case are illustrated in ***Figure 4*** by the yellow curve in (step 5). This is for illustration purposes only: actually, the load shedding does not necessarily occurs during peak load periods but rather at price peaks which do not always match peak loads. Indeed, price peaks depend not only on load but also on intermittent generation, in particular for situations with high RES penetration. Therefore, load shedding and demand shift are influenced by the "residual load" (difference between load and non-dispatchable generation such as wind, solar and must-run) rather than by the raw load. This is illustrated by ***Figure 5***, which shows for one day in the 2013 scenario the hourly load, residual load and market price in Germany (Default and MidFlex cases): it can be observed that the market price profile (red curve) matches the residual load profile (brown curve) rather than the "raw" load profile (dotted blue curve).

Figure 5. *Hourly load, residual load and market price in Germany on day 180 of the simulation (2013 scenario)*



- Then, based on the outputs of both the Default and the MidFlex cases, demand shift is calculated (step 6). The resulting new demand curve is represented in red in ***Figure 4***. Positioning demand shifts, before and after the load shedding occurs, needs some hypotheses and requires a robust approach. This is detailed in section 3.2.2 below.
- Once a new demand curve (including load shedding when prices are high enough, and shift of the corresponding energy to low residual consumption hours) has been calculated, it is implemented as an input data into the initial scenario (step 7).
- Afterwards, the modified scenario is given as an input to Optimate (step 8) with no demand flexibility modelled (it is already embedded in the scenario).
- Finally, once Optimate has run the outputs of the case “MidFlex with demand shift” can be analysed (step 9).

3.2.2 Detailed configuration of demand shift

We are computing demand shift caused by load shedding using an optimization problem that we describe below. It requires to adopt a set of hypotheses and parameters to define the constraints of the problem.

- The objective function is to minimize the variability of the residual load curve (difference between load and non-dispatchable generation). In other words, the objective is to smooth the residual load curve resulting from load shedding and demand shifts.
- The maximum amount that can be shifted to a given hour must be set. We consider here, when the residual load is positive, that this amount should be symmetrical to the shedding capacity (5% of the load in the MidFlex case, and 10% in HighFlex). When the residual load is negative we allow this amount to exceed the above-mentioned upper limits up to the absolute value of the residual load, to avoid when possible curtailing RES generation (see Figure *8* below for illustration).. We assume that strong incentives would be given to consumers to move a higher proportion of their consumption to these exceptional hours to limit RES curtailments.
- The maximum number of hours that can be used to shift consumption after load shedding occurs, and symmetrically before, is 12 hours in the MidFlex case and 24 hours in the HighFlex case.
- Consumption shifts must not create new peaks in residual consumption: for a given hour h, the final consumption, if higher than the initial one, must not exceed the initial consumption of the hours between h-4 and h+4.

Shifting 100% of the load shed (“full demand shift” or FDS) while respecting all these constraints is not always feasible: for cases with no solution to the optimization problem the amount of the demand shifted to low-price hours has not reached 100% of the energy shed during high-price hours. To measure the magnitude of such situations, the proportion of energy not shifted following load shedding has been monitored. ***Table 4*** below shows the yearly values of this indicator for each case run and each country: in most cases, this proportion is 0%; in other cases, it lies between

0.1% and 1% depending on the scenarios and the cases. The maximum proportion of energy not shifted, 1%, is reached in France (2013 scenario, HighFlex case). Therefore, the actual amount of demand shift as modelled here lies between 99% and 100%, which does not change significantly the purpose of our study: we still consider than a full demand shift (FDS) is modelled.

Table 4. *Proportion of energy not shifted following load shedding, per case run and per country*

	2013 scenario		2020 standard scenario		2020 RES+ scenario	
	MidFlex, FDS	HighFlex, FDS	MidFlex, FDS	HighFlex, FDS	MidFlex, FDS	HighFlex, FDS
AT	0.0%	0.2%	0.1%	0.1%	0.0%	0.4%
BE	0.0%	0.1%	0.0%	0.0%	0.0%	0.3%
FR	0.2%	1.0%	0.5%	0.5%	0.4%	1.0%
DE	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
GB	0.1%	0.1%	0.0%	0.0%	0.0%	0.1%
IT	0.0%	0.0%	0.3%	0.3%	0.0%	0.3%
NL	0.0%	0.1%	0.0%	0.0%	0.1%	0.3%
PT	0.3%	0.1%	0.5%	0.5%	0.0%	0.0%
ES	0.4%	0.5%	0.4%	0.4%	0.8%	0.9%
CH	0.0%	0.0%	0.0%	0.0%	0.2%	0.6%

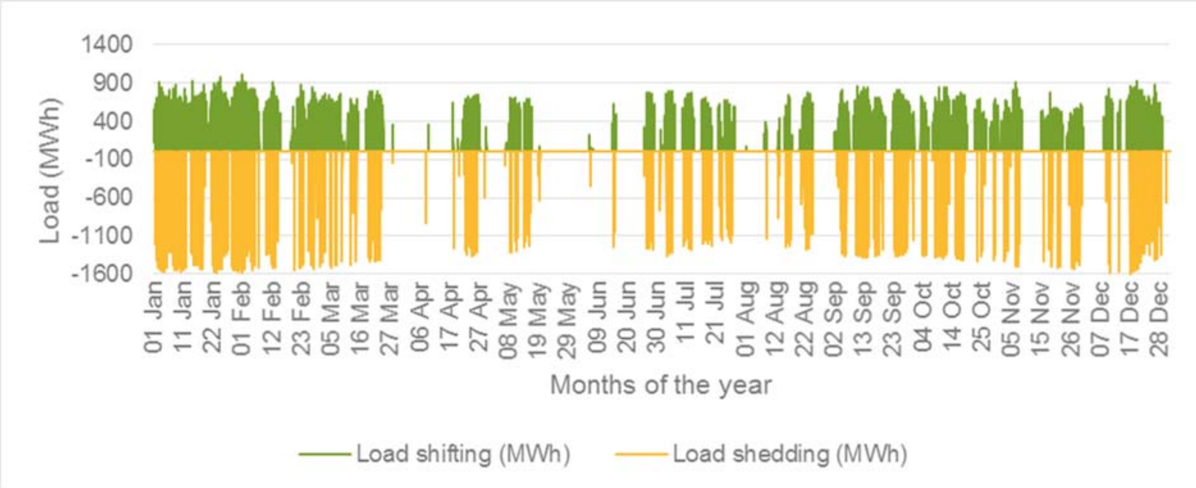
3.3 Illustration of load shedding and demand shift behaviour

The methodology described in the previous section has been implemented for the MidFlex and HighFlex cases within the three scenarios (2013, 2020 standard and 2020 RES+).

Figure 6 illustrates how load shedding and load shifting are distributed in Belgium for the 2020 standard scenario for the HighFlex case with full demand shift (FDS). Most load shedding and load shifting occur during winter, autumn and summer[15]. One can observe that up to 1,600 MW can be shed, while around 800 MW are reported at most for each hour. Since the total amount of load shed is shifted, demand shift is spread over more hours than load shedding.

[15] This can be explained by the fact that the highest prices are observed through these seasons (winter, autumn and summer) of the year. As a consequence, load shedding occurs during these seasons, and by construction (considering the methodology to model demand shifts) load shifting occurs mostly also during these seasons.

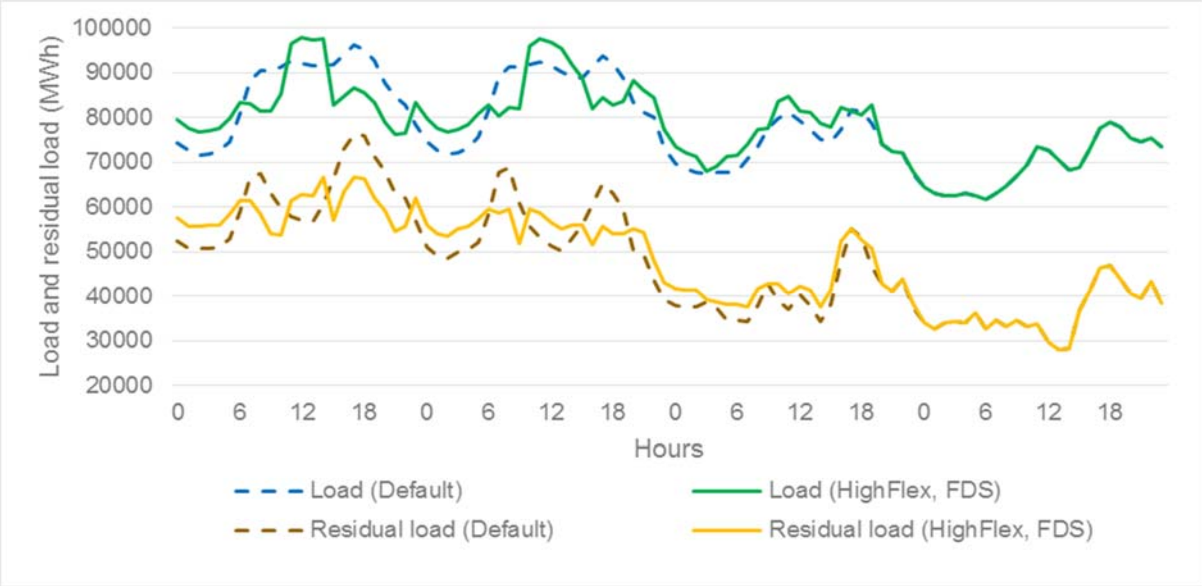
Figure 6. *Yearly load shedding and load shifting time series in Belgium (HighFlex FDS, 2020 RES+ scenario)*



Some examples have been selected to illustrate how demand shift behaves within our modelling:

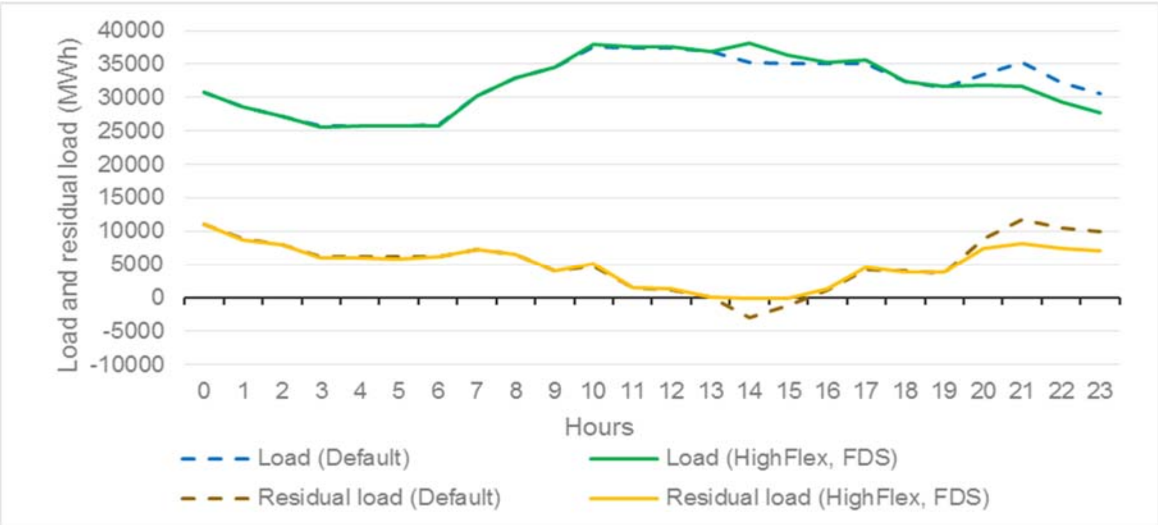
- *Figure 7* below illustrates how load shedding and demand shift behave during four consecutive days (two week-days and the week-end) in Germany for the 2020 standard scenario. Here, we observe that shifting can occur after load shedding occurs, and symmetrically before (load with Full Demand Shift – FDS - represented by the green curve in *Figure 7*, compared to the Default load represented by the dotted blue curve). This allows smoothing the residual load curve as configured in the optimization program (section 3.2.1): this is represented by the yellow curve in *Figure 7*, to be compared to the Default residual load represented by the dotted brown curve. By contrast, the “raw” load curve is not necessarily smoothed since the market price profile matches the residual load profile rather than the “raw” load profile (as previously illustrated by *Figure 5*). It can be observed in *Figure 7* that the peaks occurring in residual load curve (Default case, dotted brown curve) are shaved in the HighFlex case with FDS (yellow curve), while the valleys during week-days are partially fulfilled. Demand shift does not occur in a limited manner from week-days to week-ends, since we have set for the HighFlex case that load can be shifted to at most 24 hours before or after load shedding occurs (12 hours in the MidFlex case).

Figure 7. *Hourly load and residual load in Germany on days 332 to 336 of the simulation (2020 standard scenario)*



- Figure *8* below illustrates how demand shift behaves in case of negative residual load. It highlights the mismatch between the raw load and residual load profiles. As configured in the optimization program, the amount of demand shift during hours with negative residual load allows increasing the residual load up to zero, thus avoiding RES curtailment.

Figure 8. *Hourly load and residual load in Spain on day 89 of the simulation (2020 RES+ scenario)*



4 IMPACTS OF THE DEPLOYMENT OF DEMAND FLEXIBILITY

In this chapter, the impact of the deployment of demand flexibility, along four different variants, are assessed by comparison with Default cases where no demand flexibility is possible, this for three scenarios. This assessment is performed for the five families of indicators previously introduced:

- Generation mix,
- Costs and profits,
- Market prices,
- Sustainability,
- Cross-border market integration.

To avoid confusion, for each family of indicators the cases WITHOUT demand shift are always analysed first. The cases WITH demand shift are analysed in a separate section.

4.1 Quantitative evaluation of demand flexibility development on the generation mix

4.1.1 Generation mix global indicators

Table 5 shows the impact of the studied demand flexibility options WITHOUT demand shift on the generation mix global indicators, compared to the Default cases (no demand flexibility), for the three scenarios.

As explained in D4.2, the score for negative residual load is the average value, over all countries, of the number of hours during which residual load is negative: this means that domestic load is covered by non-dispatchable generation (must-run, solar and wind). It must also be recalled that regarding the generation from oil units, it is lower than what is measured in real-life: this is because only the day-ahead module of OPTIMATE is considered for the studies. In real-life, oil units significantly intervene in shorter-term markets such as intraday and balancing.

Table 5 shows that demand flexibility has an impact mainly on the production coming from fossil fuels. Not only the production from gas units is decreased (between 2.1% and 6.4% for MidFlex, and between 6.1% and 13.6% for HighFlex), but also the production from coal units in particular within the HighFlex cases (between 0.8% and 2.7%). There are significant differences between the countries: they are detailed in sections 4.1.2 and 4.1.3 below.

Regarding the consumption in general, it is impacted by 0.3% to 1.5% depending on the scenarios and the cases. Those figures seem low, but they actually are consistent with the specifications of the study, since at most 10% of load shedding occur during 10% of hours.

Table 5. *Impact of demand flexibility development WITHOUT demand shift on the generation mix global indicators (compared to the default cases)*

	2013 scenario			2020 standard scenario			2020 RES+ scenario		
	Default case	**MidFlex** *(Variation / default)*	**HighFlex** *(Variation / default)*	**Default case**	**MidFlex** *(Variation / default)*	**HighFlex** *(Variation / default)*	**Default case**	**MidFlex** *(Variation / default)*	**HighFlex** *(Variation / default)*
Generation from RES (TWh)	**885**	**884** *-0.1%*	**883** *-0.2%*	**1,152**	**1,149** *-0.3%*	**1,143** *-0.7%*	**1,366**	**1,364** *-0.1%*	**1,360** *-0.4%*
Wind	**159**	**159** *0.003%*	**159** *0.02%*	**335**	**335** *0.016%*	**335** *0.01%*	**461**	**461** *0%*	**461** *0%*
Solar	**82**	**82** *0.004%*	**82** *0.001%*	**134**	**134** *0.0003%*	**134** *-0.002%*	**190**	**190** *0%*	**190** *0%*
Other RES	**885**	**884** *-0.1%*	**883** *-0.2%*	**1,151**	**1,148** *-0.3%*	**1,143** *-0.7%*	**1,365**	**1,363** *-0.1%*	**1,359** *-0.4%*
Generation from nuclear (TWh)	**788**	**787** *-0.03%*	**787** *-0.09%*	**805**	**804** *-0.007%*	**804** *-0.004%*	**682**	**682** *-0.01%*	**681** *-0.11%*
Generation from fossil fuels (TWh)	**791**	**784** *-0.9%*	**773** *-2.2%*	**622**	**610** *-2.0%*	**591** *-5.0%*	**528**	**520** *-1.5%*	**505** *-4.3%*
Coal	**676**	**673** *-0.4%*	**670** *-0.8%*	**494**	**490** *-0.8%*	**481** *-2.7%*	**280**	**277** *-0.9%*	**272** *-2.6%*
Gas	**115**	**110** *-4.0%*	**103** *-10.6%*	**128**	**120** *-6.4%*	**111** *-13.6%*	**248**	**243** *-2.1%*	**233** *-6.1%*
Oil	**0.0002**	**0** *-100%*	**0** *-100%*	**0**	**0** *-*	**0** *-*	**0.0025**	**0.0025** *0%*	**0.0027** *6.7%*
Total load (TWh)	**2,463**	**2,455** *-0.3%*	**2,443** *-0.8%*	**2,579**	**2,563** *-0.6%*	**2,539** *-1.5%*	**2,575**	**2,565** *-0.4%*	**2,546** *-1.1%*
Score for negative residual load	**396**	**395** *-0.1%*	**388** *-1.9%*	**457**	**458** *0.1%*	**457** *0%*	**760**	**761** *0.2%*	**769** *1.2%*

4.1.2 Impact of demand flexibility on gas-based production per country

Table 6 shows the electricity production from gas in TWh per year, for each country within our scope.

In all countries, production from gas is significantly impacted by demand flexibility: this was expected since gas is one of the main peak generation means. Still, in countries with the highest amounts of generation from gas (Italy, Great-Britain, Netherlands and Germany), the relative impact of demand flexibility is limited, since in those countries gas is not only used during peak hours but is actually a semi-base means.

Table 6. *Impact of demand flexibility on yearly gas-based generation per country, for the three scenarios (TWh)*

	2013 scenario			2020 standard scenario			2020 RES+ scenario		
	Default case	**MidFlex** *(Variation / default)*	**HighFlex** *(Variation / default)*	**Default case**	**MidFlex** *(Variation / default)*	**HighFlex** *(Variation / default)*	**Default case**	**MidFlex** *(Variation / default)*	**HighFlex** *(Variation / default)*
AT	**0.15**	**0.09** *-39.4%*	**0.08** *-44.9%*	**15.6**	**15.3** *-1%*	**14.6** *-6%*	**52.5**	**52.4** *-0.3%*	**52.3** *-0.5%*
BE	**3.9**	**3.3** *-16.2%*	**2.6** *-33.8%*	**5.8**	**5.6** *-3.3%*	**5.2** *-10.8%*	**15.1**	**14.9** *-1.7%*	**14.1** *-6.5%*
FR	**2.74**	**2.54** *-7.3%*	**1.64** *-39.9%*	**5**	**5** *-7.6%*	**4** *-17.4%*	**6.9**	**6.5** *-6.4%*	**5.5** *-20.6%*
DE	**10.6**	**9.5** *-10.5%*	**8.2** *-22.7%*	**20.9**	**20.2** *-3.5%*	**19.7** *-5.8%*	**30.6**	**29.1** *-4.8%*	**27.4** *-10.3%*
GB	**37.3**	**36.8** *-1.3%*	**35.7** *-4.4%*	**10.5**	**9.3** *-11.3%*	**7.8** *-26.4%*	**42.8**	**41.9** *-2.1%*	**40.6** *-5.2%*
IT	**40.7**	**39.6** *-2.6%*	**38.2** *-6.1%*	**41.4**	**38.4** *-7.2%*	**36.4** *-12.0%*	**50.2**	**49.1** *-2.1%*	**46.2** *-7.9%*
NL	**17.5**	**16.7** *-4.9%*	**14.7** *-16.1%*	**19.2**	**18.2** *-5.4%*	**16.9** *-12.3%*	**30.0**	**29.5** *-1.7%*	**27.9** *-6.9%*
PT	**0.05**	**0.03** *-32.2%*	**0.03** *-43.5%*	**1.4**	**0.8** *-41.8%*	**0.4** *-70.1%*	**8.2**	**8.2** *-0.3%*	**8.2** *-0.3%*
ES	**1.8**	**1.7** *-7.2%*	**1.5** *-19.8%*	**8.0**	**7.1** *-10.5%*	**5.4** *-32.2%*	**11.6**	**11.1** *-4.1%*	**10.4** *-9.9%*

4.1.3 Impact of demand flexibility on coal-based production per country

Table 7 shows the coal production in TWh per year, for each country within our scope[16]. In countries with the highest coal generation (Germany, Great-Britain, Italy and Spain), demand flexibility has little impact on coal production. It is in France and in Portugal that the deployment of demand flexibility should impact the most the generation from coal.

Regarding France, at first sight the decrease in coal generation is surprising, since coal is not one of the main generation source, and peak load is covered by other means (gas, hydro dams). This is confirmed by ***Figure 9***, which shows for the 2013 scenario the average over the year of:

- the hourly production per type of source,
- in yellow, the hourly load for the Default case (dotted line) and the HighFlex case (solid line),
- in red, the hourly load + the net exports for the Default case (dotted line) and the HighFlex case (solid line).

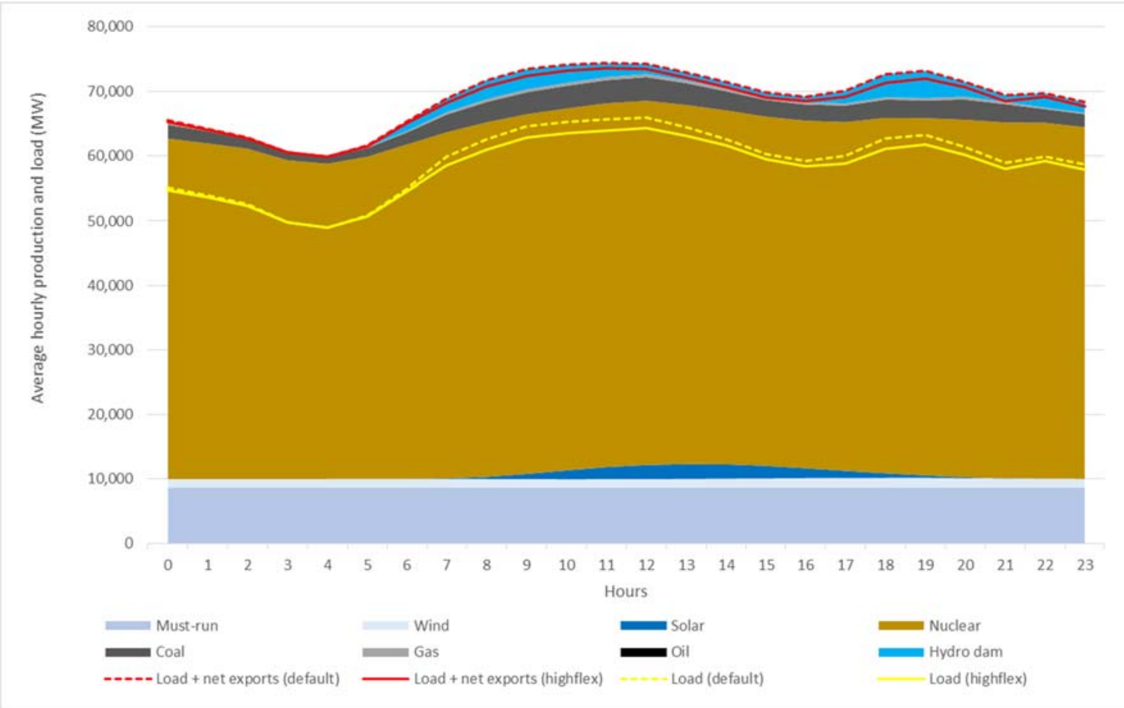
[16] Within our modelling, coal capacity in Belgium which is too little had to be neglected.

Table 7. *Impact of demand flexibility on yearly coal-based generation per country, for the three scenarios (TWh)*

	2013 scenario			2020 standard scenario			2020 RES+ scenario		
	Default case	MidFlex (Variation / default)	HighFlex (Variation / default)	Default case	MidFlex (Variation / default)	HighFlex (Variation / default)	Default case	MidFlex (Variation / default)	HighFlex (Variation / default)
AT	**4.082**	**4.083** *0.01%*	**4.07** *-0.22%*	**6.03**	**5.99** *-1.0%*	**5.89** *-3.3%*	**4.17**	**4.16** *-0.2%*	**4.13** *-0.9%*
FR	**22.1**	**21.0** *-4.9%*	**18.4** *-16.7%*	**12.8**	**12.1** *-3.4%*	**10.0** *-12.7%*	**2.02**	**1.79** *-1.0%*	**1.06** *-4.3%*
DE	**339.0**	**338.7** *-0.1%*	**338** *-0.3%*	**227**	**225** *-0.4%*	**222** *-1.5%*	**152**	**150** *-0.4%*	**149** *-1.0%*
GB	**134.5**	**134.5** *0.1%*	**134.7** *0.2%*	**73.3**	**73.1** *-0.1%*	**71.9** *-1.0%*	**4.46**	**3.79** *-0.5%*	**2.79** *-1.2%*
IT	**93.4**	**92.8** *-0.6%*	**93.1** *-0.3%*	**111.1**	**110.5** *-0.6%*	**109.7** *-1.4%*	**89.35**	**89.27** *-0.1%*	**88.8** *-0.6%*
NL	**57.0**	**57.1** *0.1%*	**57.3** *0.5%*	**37.4**	**36.4** *-1.7%*	**35.6** *-3.2%*	**27.4**	**27.2** *-0.4%*	**26.9** *-1.0%*
PT	**2.12**	**2.08** *-2.1%*	**1.84** *-13.1%*	**1.46**	**1.30** *-7.6%*	**0.51** *-45.0%*	**0**	**0**	**0**
ES	**23.6**	**23.0** *-2.6%*	**22.9** *-3.0%*	**25.3**	**25.2** *-0.3%*	**25.2** *-0.4%*	**0.41**	**0.32** *-0.4%*	**0.27** *-0.6%*

Average profiles in ***Figure 9***, do not help understanding why coal-based production is particularly impacted in France compared to other countries.

Figure 9. *Average hourly production and load in France (2013 scenario)*



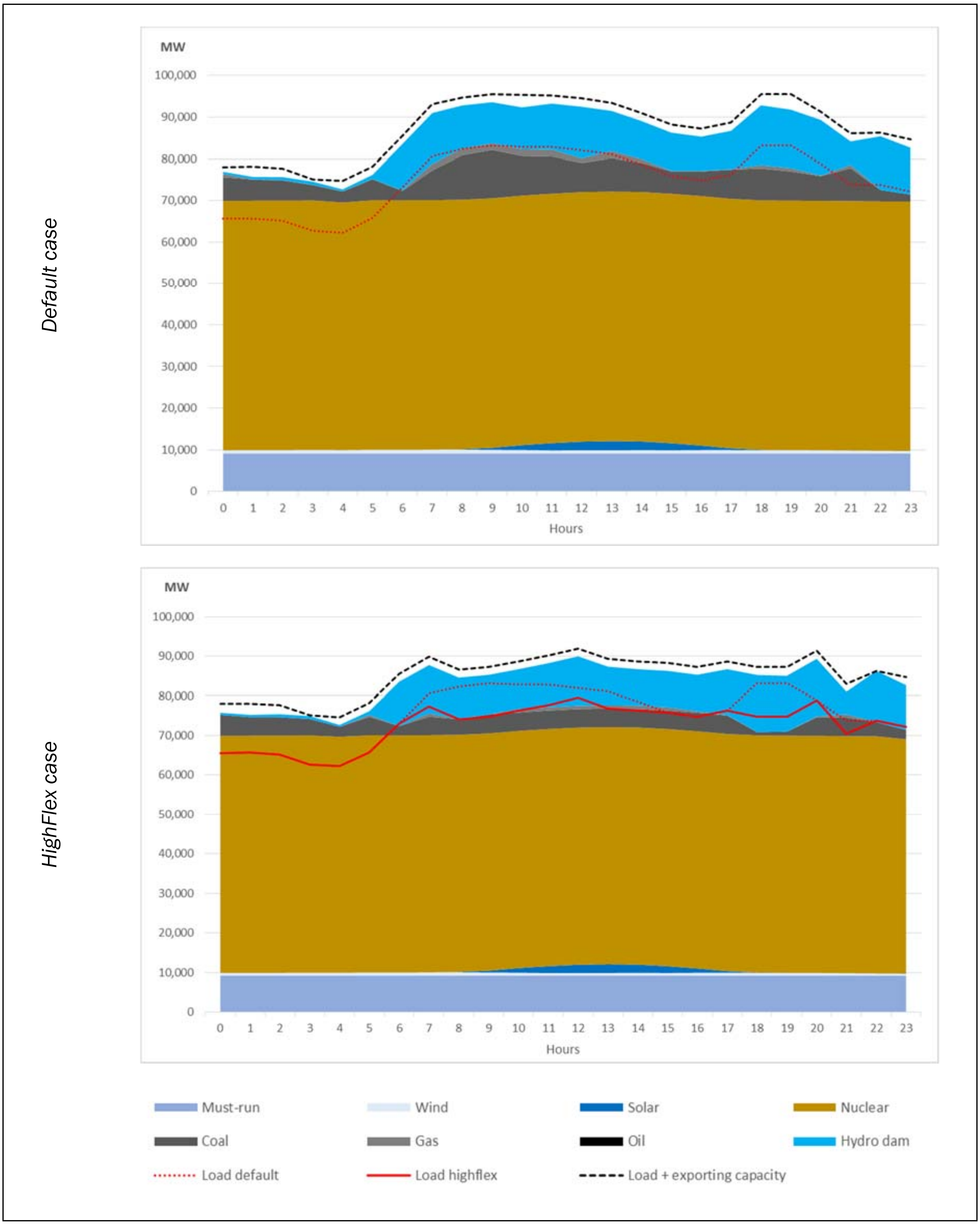
Actually, having a look on specific days (those during which coal-based production is actually impacted) gives some clues, as illustrated on Figure *10*:

- The top graph shows the hourly production and consumption in the Default case of the 2013 scenario;
- The bottom graph shows the hourly production and consumption in the HighFlex case of the 2013 scenario.

It appears that coal-based production follows the load: when load sheds, coal production is similarly reduced. It could have been expected that coal production would be maintained and exported, since in this example cross-border capacities are not fully saturated (dotted black line, above the total production); but it does not. This can be interpreted by the fact that this production is not competitive compared to the one of neighbouring countries.

In conclusion, the impact of load flexibility on the coal-based production in France illustrates the global interrelations between production costs and constraints, prices and cross-border flows: the impact of demand flexibility on the generation mix within a given country cannot be interpreted in an isolated manner (see also section 4.5)

Figure 10. *Hourly production and load in France for day 35 (2013 scenario)*



4.1.4 Impact of consumption shift caused by load shedding on generation mix indicators

Table 8 shows the impact of the studied demand flexibility options WITH demand shift on the generation mix global indicators, compared to the Default cases (no demand flexibility), for the three scenarios. It should be compared to *Table 5* which shows these indicators WITHOUT demand shift.

Table 8. *Impact of demand flexibility development WITH demand shift on the generation mix global indicators (compared to the Default cases)*

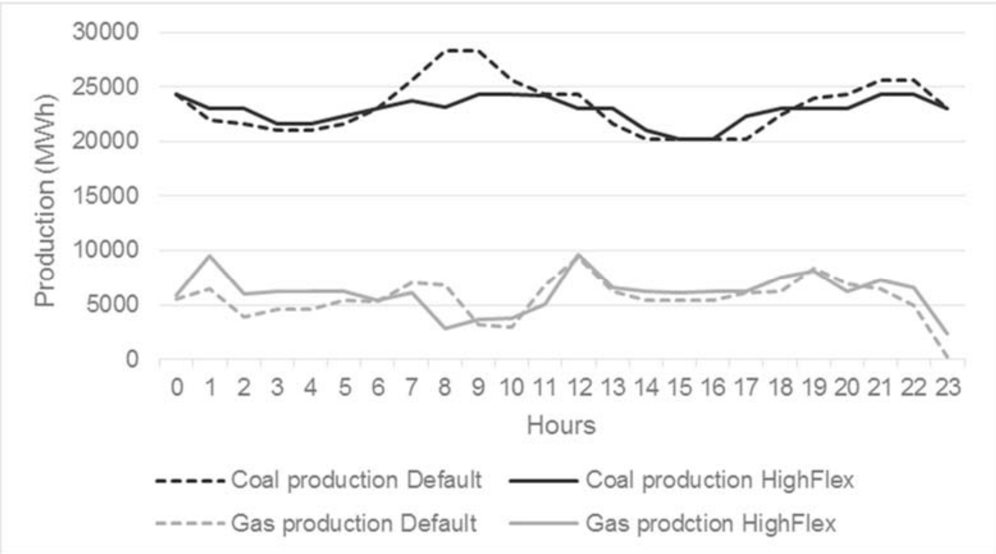
	2013 scenario			2020 standard scenario			2020 RES+ scenario		
	Default case	MidFlex, FDS *(Variation / default)*	HighFlex, FDS *(Variation / default)*	Default case	MidFlex, FDS *(Variation / default)*	HighFlex, FDS *(Variation / default)*	Default case	MidFlex, FDS *(Variation / default)*	HighFlex, FDS *(Variation / default)*
Generation from RES (TWh)	885	888 *0.4%*	888 *0.3%*	1,152	1,152 *0.003%*	1,152 *0.003%*	1,366	1,364 *-0.1%*	1,361 *-0.4%*
Wind	159	159 *0.0298%*	159 *0.06%*	335	335 *0.04%*	335 *0.04%*	461	461 *0.025%*	461 *0.045%*
Solar	82	82 *0.007%*	82 *0.009%*	134	134 *0.008%*	134 *0.008%*	190	190 *0.0099%*	190 *0.021%*
Other RES	885	888 *0.4%*	887 *0.3%*	1,151	1,151 *0.0%*	1,151 *0.0%*	1,365	1,364 *-0.1%*	1,360 *-0.4%*
Generation from nuclear (TWh)	788	788 *0.0%*	789 *0.1%*	805	805 *0.1%*	805 *0.1%*	682	679 *-0.4%*	680 *-0.2%*
Generation from fossil fuels (TWh)	791	785 *-0.6%*	783 *-1.0%*	622	616 *-1.0%*	616 *-1.0%*	528	527 *-0.2%*	523 *-0.9%*
Coal	676	674 *-0.3%*	673 *-0.4%*	494	492 *-0.5%*	492 *-0.5%*	280	278 *-0.7%*	276 *-1.2%*
Gas	115	111 *-2.9%*	109 *-4.7%*	128	124 *-3.0%*	124 *-3.0%*	248	249 *0.5%*	247 *-0.5%*
Oil	0.0002	0 *-100%*	0 *-100%*	0	0 *-*	0 *-*	0.0025	0.0020 *-20%*	0.0019 *-26.7%*
Total load (TWh)	2,463	2,462 *-0.1%*	2,459 *-0.2%*	2,579	2,573 *-0.2%*	2,573 *-0.2%*	2,575	2,570 *-0.2%*	2,564 *-0.4%*
Score for negative residual load	396	402 *1.6%*	406 *2.5%*	457	460 *0.6%*	460 *0.7%*	760	806 *6.0%*	807 *6.2%*

Table 8 shows that demand flexibility WITH demand shift has an impact on the production coming from fossil fuels and also on the production coming from RES. The production from gas units WITH demand shift is less impacted (between -3% and +0.5% for MidFlex, and between -4.7 % and -0.5% for HighFlex), compared to the production WITHOUT demand shift (between -6.4% and -2.1% for MidFlex, and between -13.6% and -6.1% for HighFlex). The same behaviour occurs for the coal-based production. Regarding the generation from RES, demand shift make it increase mainly within the 2013 scenario due to hydraulic production. We can also note a slight increase of solar and wind production, corresponding to the fact that demand shift allows for limiting RES curtailments in case of high RES production combined to low consumption (notably during negative residual load hours). Due to the modelling hypotheses which consider neither local network constraints nor close to real-time markets, this effect is probably underestimated: in real life,

demand activation during negative residual load hours should have a greater impact on RES generation.[17]

As previously there are significant differences between the countries, but trends appear. We observe that the gas and the coal production are smoother WITH demand shift. More precisely, WITH demand shift, the standard deviation of these time series are lower than WITHOUT demand shift. This is presented by ***Figure 11*** which exemplifies one day in Germany.

Figure 11. *Coal-based and gas-based production in Germany on day 187 of the simulation (2020 RES+ scenario)*



Finally, it can be noticed that the score for negative residual load is impacted in an unexpected manner by demand shifts: the number of hours with negative residual load increases when demand shift occurs, although the existence of demand shift should on the contrary decrease it since within our modelling demand shifts are preferably positioned during hours with low, possibly negative residual hours. In fact, the increase in the global indicator comes from two countries only: Spain and Portugal. This paradoxical effect is closely linked with cross-border impacts of load flexibility and demand shifts, which are studied in section 4.5 (with a focus on the Spanish-French border in subsection 4.5.5).

[17] **Studying such impact, by modelling local network constraints and all market segments from day-ahead to real-time, could be the purpose of future studies to be done with OPTIMATE.**

4.2 Quantitative evaluation of demand flexibility development on costs and profits

4.2.1 Costs and profits global indicators

Table 9 shows the impact of the studied demand flexibility options WITHOUT demand shift on the costs and profits' global indicators, compared to the Default cases (no demand flexibility), for the three scenarios.

Table 9. *Impact of demand flexibility development WITHOUT demand shift on the costs and profits' global indicators (compared to the Default cases)*

	2013 scenario			2020 standard scenario			2020 RES+ scenario		
	Default case	**MidFlex** *(Variation / default)*	**HighFlex** *(Variation / default)*	**Default case**	**MidFlex** *(Variation / default)*	**HighFlex** *(Variation / default)*	**Default case**	**MidFlex** *(Variation / default)*	**HighFlex** *(Variation / default)*
Thermal generation costs (M€)	34,793	34,335 *-1.3%*	33,649 *-3.3%*	39,280	38,346 *-2.4%*	37,209 *-5.3%*	42,975	42,162 *-1.9%*	40,814 *-5.0%*
Total producer revenues (M€)[18]	86,388	83,539 *-3.3%*	81,540 *-5.6%*	122,714	120,412 *-1.9%*	116,561 *-5.0%*	146,563	144,678 *-1.3%*	142,497 *-2.8%*
Wind	5,055	4,949 *-2.1%*	4,864 *-3.8%*	14,347	14,249 *-0.7%*	14,051 *-2.1%*	22,722	22,639 *-0.4%*	22,558 *-0.7%*
Solar	2,906	2,853 *-1.8%*	2,818 *-3.0%*	6,356	6,304 *-0.8%*	6,215 *-2.2%*	10,013	9,971 *-0.4%*	9,927 *-0.9%*
Other RES	21,353	20,697 *-3.1%*	20,292 *-5.0%*	32,727	32,194 *-1.6%*	31,327 *-4.3%*	41,393	40,915 *-1.2%*	40,809 *-1.4%*
Thermal	57,074	55,041 *-3.6%*	53,567 *-6.1%*	69,283	67,665 *-2.3%*	64,968 *-6.2%*	72,435	71,153 *-1.8%*	69,203 *-4.5%*
Producer revenues per MWh generated (€/MWh)	35.41	34.04 *-3.9%*	33.36 *-5.8%*	48.67	48.10 *-1.2%*	47.16 *-3.1%*	58.89	58.42 *-0.5%*	58.08 *-1.2%*
Wind	33.16	32.72 *-1.3%*	32.07 *-3.3%*	43.95	42.91 *-2.4%*	41.63 *-5.3%*	50.21	49.26 *-1.9%*	47.69 *-5.0%*
Solar	36.10	34.74 *-3.8%*	34.24 *-5.1%*	46.95	46.65 *-0.6%*	46.05 *-1.9%*	53.10	52.92 *-0.4%*	52.71 *-0.7%*
Other RES	34.88	33.47 *-4.0%*	32.84 *-5.9%*	48.23	47.76 *-1.0%*	46.91 *-2.7%*	58.69	58.22 *-0.8%*	58.37 *-0.6%*
Thermal	37.31	35.88 *-2.9%*	35.09 *-5.0%*	52.88	52.12 *-1.4%*	51.12 *-4.2%*	65.29	64.65 *-1.0%*	63.92 *-2.4%*
Consumer surplus (bn€)	23,112	23,089 *-0.1%*	23,027 *-0.4%*	24,130	24,094 *-0.1%*	23,980 *-0.6%*	24,105	24,070 *-0.1%*	23,975 *-0.5%*

Demand flexibility clearly impacts the thermal generation costs, since in general demand shedding will be applied when peak units are running (mainly based on fossil fuels). This impact increases:

- With an increasing the development of demand response (from mid to high development), and
- With an increasing RES penetration (from scenarios 2013 to 2020 standard and RES+).

Within the estimation provided by our studies, electricity generation costs could be decreased by 458 to 1,143 million of euros in the reference scenario, 934 to 2,071 million of euros in the 2020

[18] In this study, RES producers are supposed to receive no Feed-in-Tariffs: they are exposed to market prices as other producers.

context (2020 standard scenario), and 813 to 2,161 million of euros if 2020 objectives are surpassed (2020 RES+ scenario).[19]

In terms of revenues, thermal producers are obviously impacted. First, as all other producers their revenues are impacted by the decrease in market prices due to load shedding: this impact can be measured by the decrease in average revenues per MWh generated (between -1.0% and -5.0%). Second, the annual volume of energy generated by thermal plants also decreases with demand flexibility, as observed in section 4.1: this is why the impact on thermal producers in terms of annual revenues is higher (between -1.8% and -6.2%).

The revenues of other producers (RES) are also impacted by the price shaving due to demand flexibility. Wind and solar producers are impacted in different ways: this is detailed in section 0 below.

Finally, the consumer surplus[20] also decreases with increasing deployment of demand flexibility. This is not an obvious impact since the deployment flexibility has logically two opposite impacts on consumer surplus: on the one hand, the decrease in market prices caused by load shedding should have a positive impact on the consumer surplus (price effect); on the other hand, the decrease in consumption should have a direct negative impact on consumer surplus (volume effect). It appears that the latter impact is greater than the former.

4.2.2 Impact of demand flexibility on wind and solar producer revenues

With high RES penetration (2020 scenarios), average wind producers revenues in €/MWh are more impacted by the deployment of demand flexibility than those of solar producers. The main reason for this difference, is that load shedding occurs mainly at hours with low residual load (combining consumption peaks and, if RES penetration is significant, low RES generation). Those hours barely correspond to solar production hours: this is illustrated by ***Figure 12*** below. In this figure, we have calculated the average load shedding per hour, over the 365 days of the year and the 11 countries within our scope (left-hand axis); we have done the same for solar generation (right-hand axis).[21]

Along the same lines, Figure ***13*** shows the total load shedding per month, over the 11 countries within our scope (left-hand axis), as well as the total monthly solar generation (right-hand axis).

[19] These savings do not take into account possible economic losses due to, for instance, decrease in the industrial production caused by load shedding done by industrial consumers.

[20] Difference between the consumers' willingness to pay and the market price, measuring the consumers' satisfaction.

[21] Within the 2020 scenarios, solar generation comes not only from photovoltaic plants, but also from concentrated solar power (CSP) plants: because CSP units are often equipped with trackers and storage facilities, the daily profile of CSP generation is significantly different from the PV profile (production is even possible after sunset); this was explained in D4.1.

Figure 12. *Average distribution of load shedding within a day, compared with average solar production, per scenario*

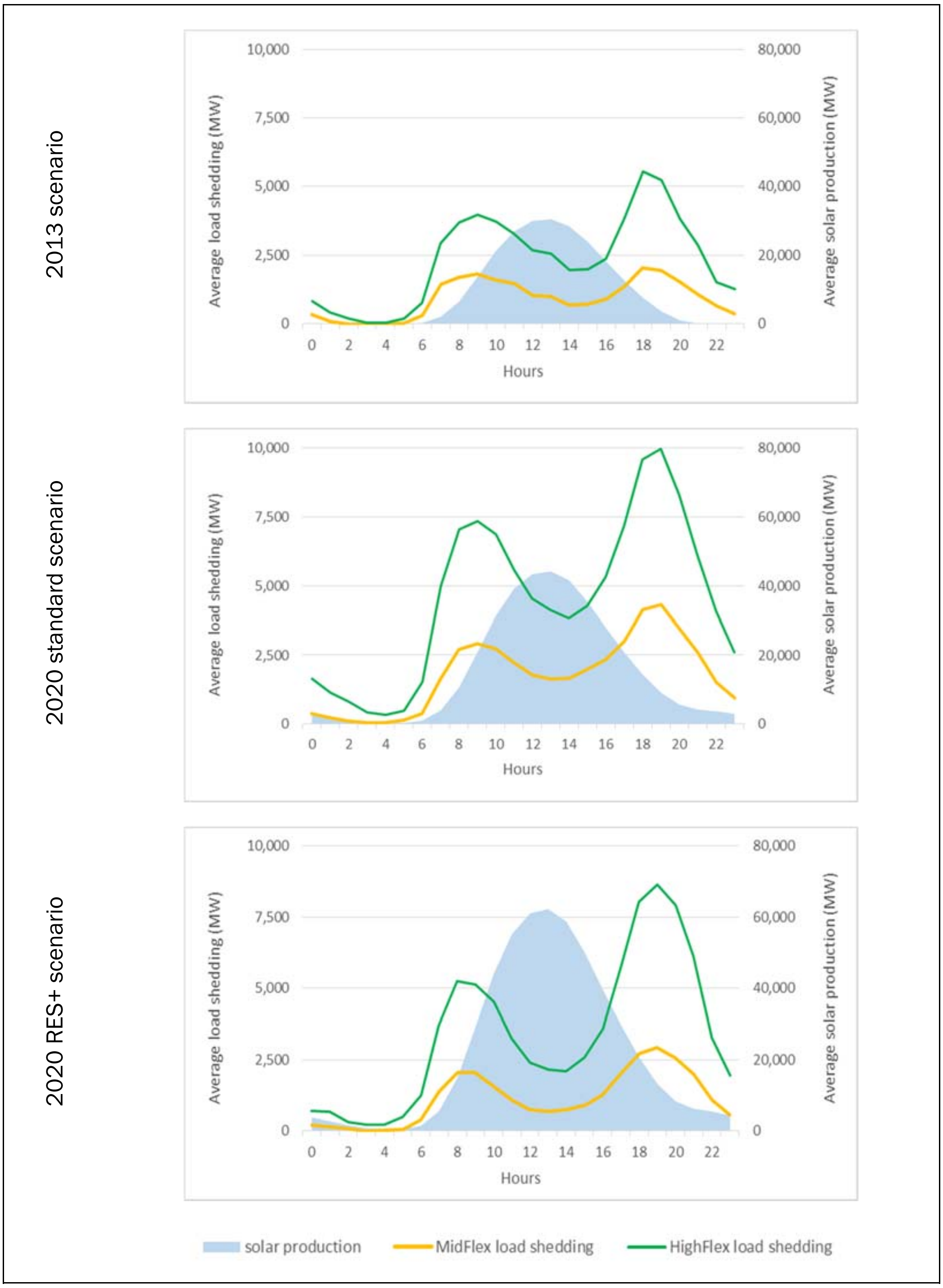
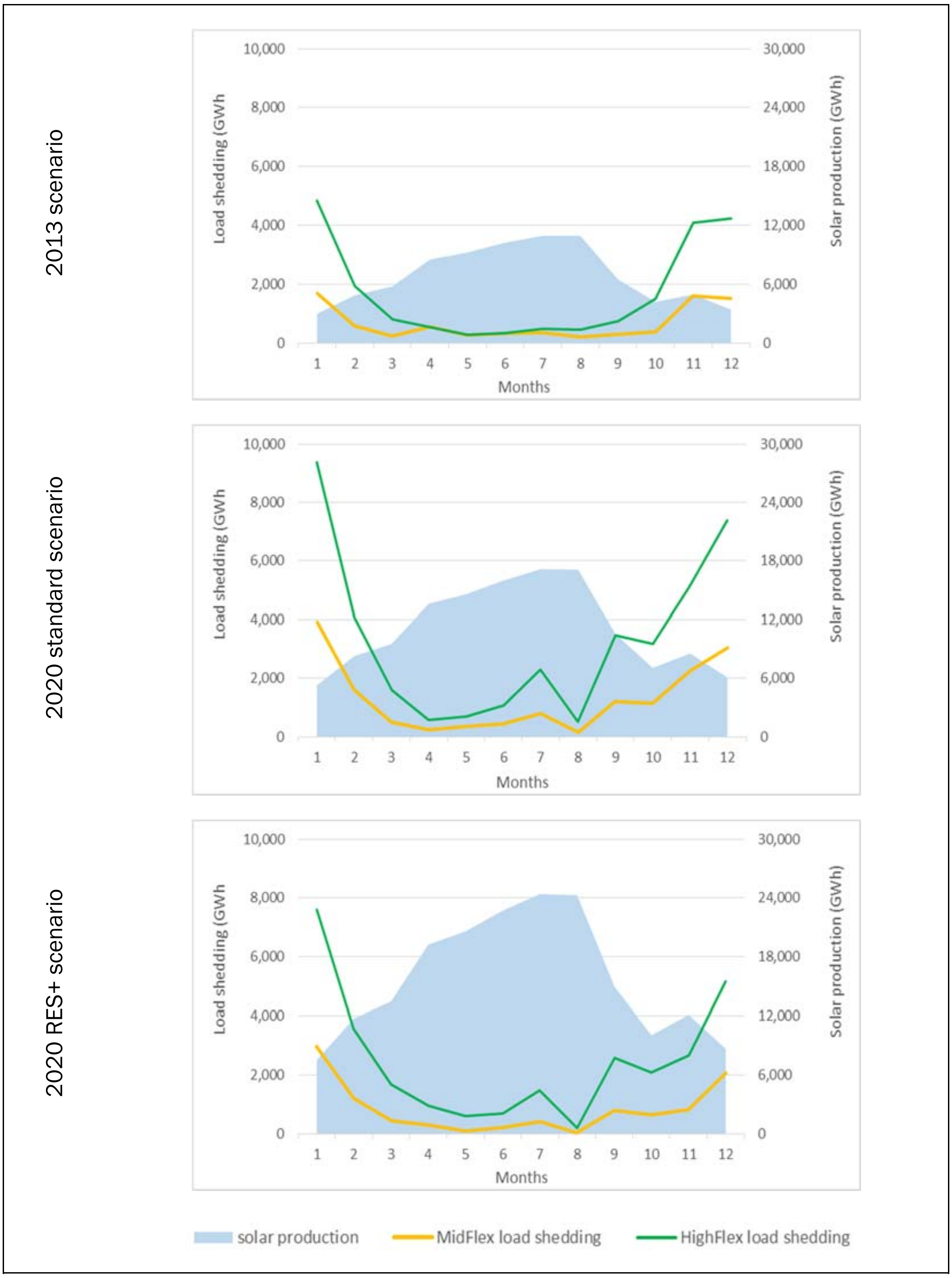


Figure 13. *Amount of load shedding per month, compared with monthly solar production, per scenario*



It can be observed within these graphs that solar production does not occur, in general, when most load shedding occurs; and this phenomenon increases with RES penetration (from 2013 scenario to 2020 RES+ scenario). In terms of time of the day, load shedding occurs indeed mostly between 6 and 10 in the morning, when solar production is not very high, and between 17 (5pm) and 21 (9pm) in the evening, when solar production is decreasing. In terms of seasons, load shedding occurs mostly during winter months, when solar production is the lowest. This is why with high levels of RES penetration, solar producers are less impacted in terms of average revenues per MWh generated than wind producers, whose average production is more flatly distributed during the day and the year.

4.2.3 Impact of consumption shift caused by load shedding on cost and profit indicators

Table 10 shows the impact of the studied demand flexibility options WITH demand shift on the costs and profits' global indicators, compared to the Default cases (no demand flexibility), for the three scenarios. It should be compared to *Table 9* which shows these indicators WITHOUT demand shift.

Compared to demand flexibility without demand shift, the annual thermal generation costs decrease to a lower extent: with demand shift, thermal generation costs are decreased by 1.1% to 4.1%, while without demand shift the decrease was between 1.3% and 5.3%. This is consistent with what was expected, since the total production with demand shift is higher than without demand shift.

The annual thermal producer revenues follows the same trend, for the same reason: with demand shift, thermal generators produce more energy than without, thus earning higher revenues. By contrast, in terms of average thermal producers revenues per MWh generated, the trend is opposite: demand shift affects negatively their average revenue per MWh generated. This can be explained by the fact that demand shift is positioned during low residual load hours, corresponding in general to low price hours; therefore, with demand shift, thermal producers sell more energy during these low price hours than without demand shift; the impact on prices of demand shift is not high enough to compensate this effect.

Table 10. *Impact of demand flexibility development WITH demand shift on the costs and profits' global indicators (compared to the Default cases)*

	2013 scenario			2020 standard scenario			2020 RES+ scenario		
	Default case	**MidFlex, FDS** *(Variation / default)*	**HighFlex, FDS** *(Variation / default)*	**Default case**	**MidFlex, FDS** *(Variation / default)*	**HighFlex, FDS** *(Variation / default)*	**Default case**	**MidFlex, FDS** *(Variation / default)*	**HighFlex, FDS** *(Variation / default)*
Thermal generation costs (M€)	**34,793**	**34,399** -1.1%	**34,200** -1.7%	**39,280**	**38,653** -1.6%	**37,672** -4.1%	**42,975**	**42,509** -1.1%	**41,823** -2.7%
Total producer revenues (M€)	**86,388**	**83,128** -3.8%	**82,401** -4.6%	**122,714**	**121,035** -1.4%	**118,267** -3.6%	**146,563**	**145,055** -1.0%	**143,891** -1.8%
Wind	**5,055**	**4,919** -2.7%	**4,904** -3.0%	**14,347**	**14,282** -0.5%	**14,172** -1.2%	**22,722**	**22,599** -0.5%	**22,606** -0.5%
Solar	**2,906**	**2,848** -2.0%	**2,836** -2.4%	**6,356**	**6,310** -0.7%	**6,248** -1.7%	**10,013**	**9,988** -0.3%	**9,912** -1.0%
Other RES	**21,353**	**20,734** -2.9%	**20,617** -3.4%	**32,727**	**32,433** -0.9%	**31,946** -2.4%	**41,393**	**41,157** -0.6%	**41,035** -0.9%
Thermal	**57,074**	**54,626** -4.3%	**54,044** -5.3%	**69,283**	**68,011** -1.8%	**65,901** -4.9%	**72,435**	**71,311** -1.6%	**70,339** -2.9%
Producer revenues per MWh generated (€/MWh)	**35.41**	**33.73** -4.7%	**33.52** -5.3%	**48.67**	**48.11** -1.1%	**47.09** -3.2%	**58.89**	**58.51** -0.6%	**58.40** -0.8%
Wind	**33.16**	**32.78** -1.1%	**32.60** -1.7%	**43.95**	**43.25** -1.6%	**42.15** -4.1%	**50.21**	**49.67** -1.1%	**48.87** -2.7%
Solar	**36.10**	**34.25** -5.1%	**34.09** -5.6%	**46.95**	**46.57** -0.8%	**46.09** -1.8%	**53.10**	**53.01** -0.2%	**52.68** -0.8%
Other RES	**34.88**	**33.18** -4.9%	**33.01** -5.4%	**48.23**	**47.77** -1.0%	**47.27** -2.0%	**58.69**	**58.55** -0.2%	**58.90** 0.4%
Thermal	**37.31**	**35.65** *-3.7%*	**35.35** *-4.7%*	**52.88**	**52.14** *-1.4%*	**47.45** *-4.8%*	**65.29**	**64.71** *-1.5%*	**64.17** *-2.7%*
Consumer surplus (Md€)	**23,112**	**23,118** 0.0%	**23,183** 0.3%	**24,130**	**23,714** -1.7%	**23,882** -1.0%	**24,105**	**23,752** -1.5%	**23,586** -2.2%

4.3 Quantitative evaluation of demand flexibility development on market prices

4.3.1 Market prices' global indicators

Table 11 shows the impact of the studied demand flexibility options WITHOUT demand shift on the market prices' global indicators, compared to the default cases (no demand flexibility), for the three scenarios.

Table 11. *Impact of demand flexibility development WITHOUT demand shift on the market prices' global indicators (compared to the Default cases)*

	2013 scenario			2020 standard scenario			2020 RES+ scenario		
	Default case	MidFlex *(Variation / default)*	HighFlex *(Variation / default)*	Default case	MidFlex *(Variation / default)*	HighFlex *(Variation / default)*	Default case	MidFlex *(Variation / default)*	HighFlex *(Variation / default)*
Average market price (€/MWh)[22]	34.63	33.71 *-3%*	33.15 *-4%*	47.64	47.21 *-1%*	46.37 *-3%*	45.46	45.06 *-1%*	44.70 *-2%*
Average daily spread (€/MWh)	34.03	23.41 *-31%*	21.02 *-38%*	26.71	25.17 *-6%*	23.23 *-13%*	43.47	38.29 *-12%*	36.57 *-16%*

Demand flexibility has a significant impact on average market prices: within all cases, this impact lies between -1% and -4%.

In addition, there are significant differences between countries. For most of the countries studied, the impact of demand flexibility on the market price lies between -1% and -5%. This is not the case of Portugal in the 2013 scenario with average prices dropping by 18% for MidFlex and 22% for HighFlex: this is detailed in section 4.3.2 below.

Regarding the average daily spread, it is a measure of the magnitude of the prices within each day: it is the average, over all days and all market areas, of the difference between the maximum price of the day within a given market area and the minimum price of the same day within the same market area. For example, if for a given day and a given market area the hourly prices lie between 25 €/MWh and 45 €/MWh, then the daily spread is 20 €/MWh.

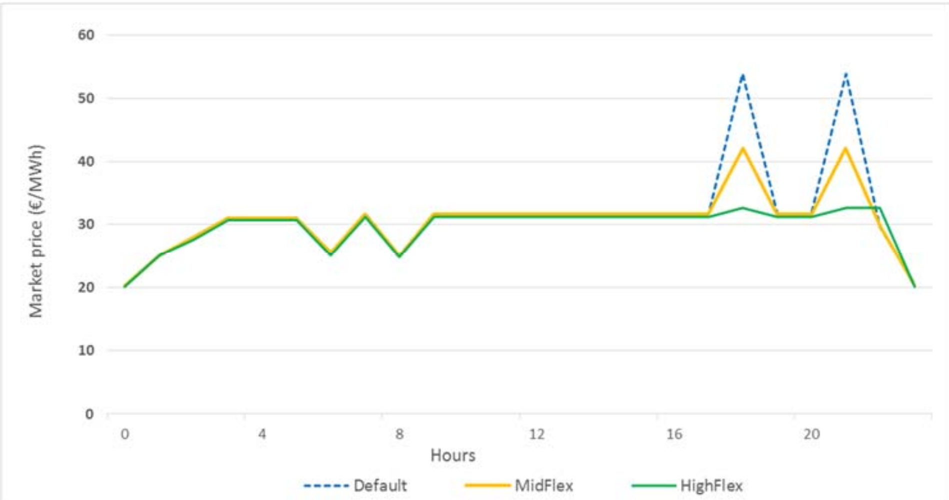
Demand flexibility has a major impact on this average daily spread, with significant differences between the three scenarios and the MidFlex and HighFlex cases. This is analysed in details in section 4.3.3 below.

[22] The average market price is weighted with the volumes of the different market areas.

4.3.2 Impact of demand flexibility on the average market prices in Portugal (2013 scenario)

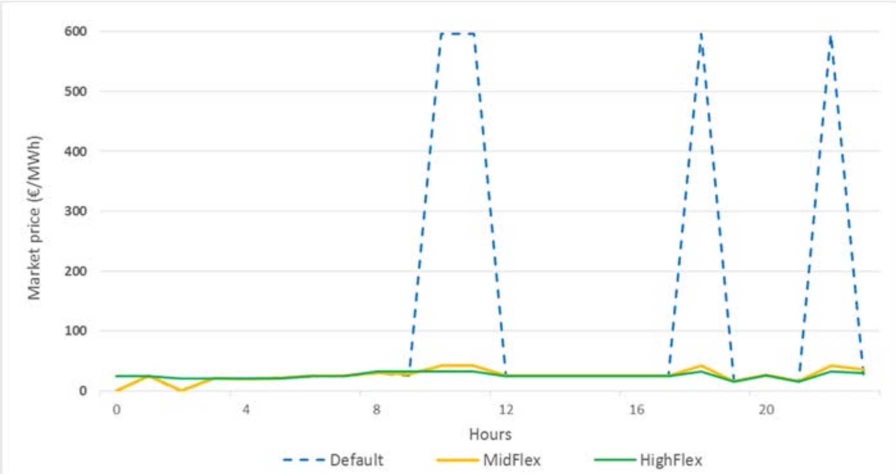
Figure *14* below shows hourly market prices in Portugal, during a "regular" day (no price peaks), illustrating the normal impact of the MidFlex and HighFlex cases on prices: for a few hours (3 within this example), the load shedding which occurs cause a significant reduction in market prices.

Figure 14. *Hourly market prices in Portugal during day 263 (2013 scenario)*



Within our modelling, Portugal is a country which frequently faces severe price peaks (82 times during the year, prices are above 500€/MWh). It is the only country facing such situations within the 2013 scenario. Figure *15* below illustrates how hourly market prices react to demand flexibility during a day facing such price peaks. Having 5% of the load shed when these peaks occur is enough, most of the time, to come back to a "regular" price situation. This is why the difference between the average price is so high between the default case and the MidFlex case (-18%).

Figure 15. *Hourly market prices in Portugal during day 60 (2013 scenario)*

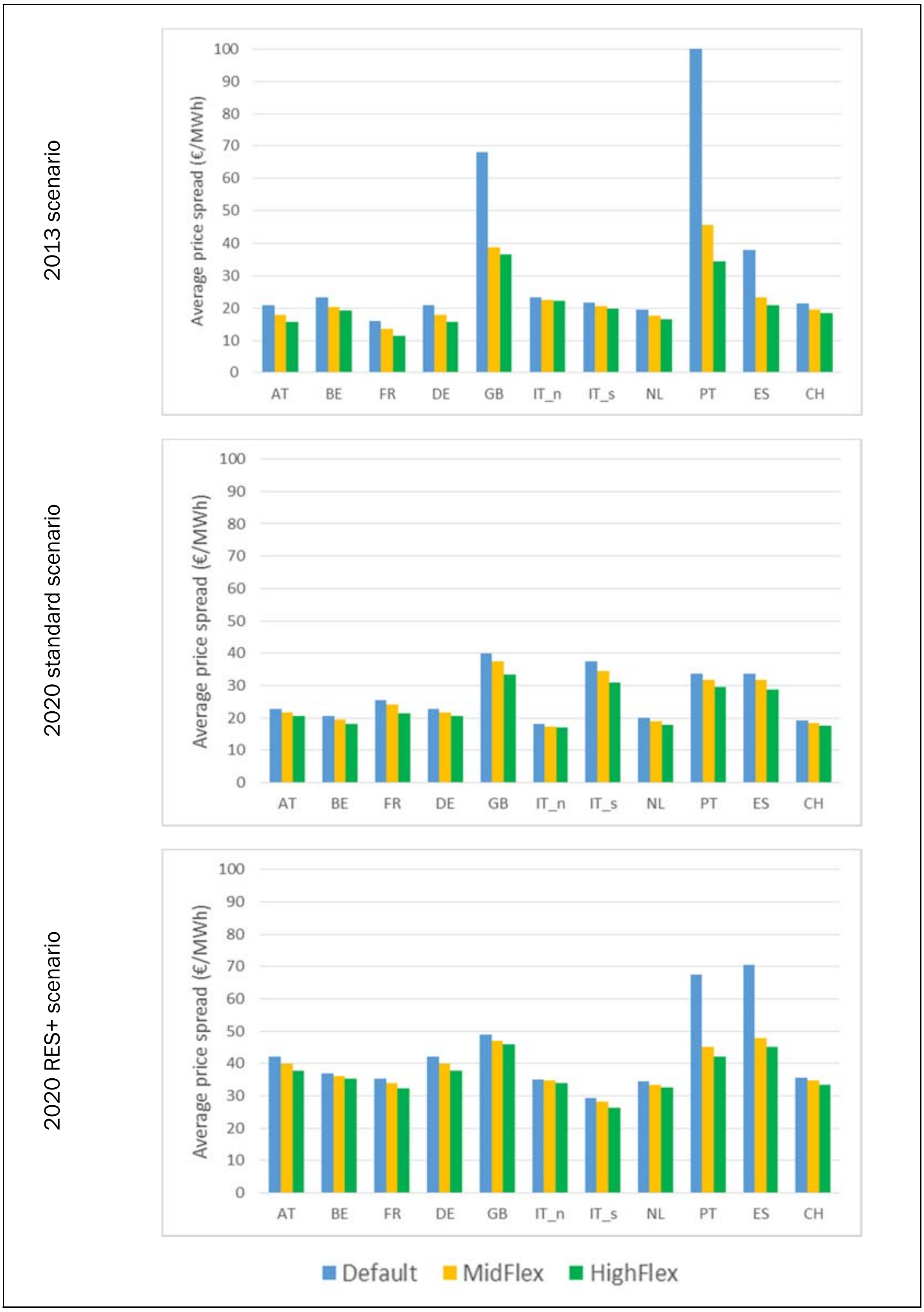


Such situation does not occur within the other two scenarios, in which Portugal has higher interconnection capacities with Spain and a different generation mix.

4.3.3 Impact of demand flexibility on the average daily spread

The impact of demand flexibility on the average daily spread is huge: this was expected since demand response allows for shaving price peaks, therefore reducing the price spreads. ***Figure 16*** shows this impact per country, for the three scenarios. It allows understanding that it is within situations with high average daily spread that the impact of demand flexibility on this spread is the highest: indeed, it is within these situations that prices can be most flattened. We have already observed that Portuguese prices in the 2013 scenario have regular peaks (section 4.3.2): shaving these peaks greatly improves the daily price spread.

Figure 16. *Average daily spread per country and per scenario*



4.3.4 Impact of consumption shift caused by load shedding on market prices indicators

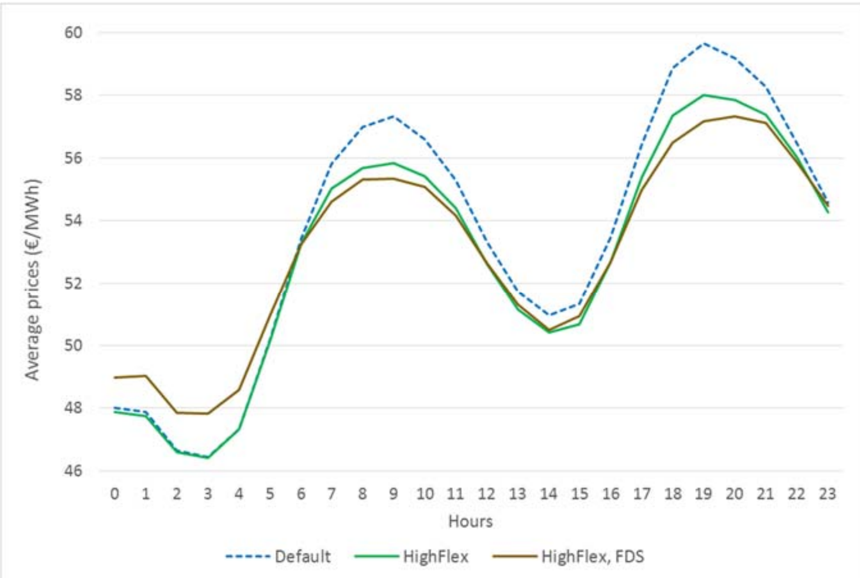
Table 12 shows the impact of the studied demand flexibility options WITH demand shift on the market prices' global indicators, compared to the Default cases (no demand flexibility), for the three scenarios. It should be compared to *Table 11* which shows these indicators WITHOUT demand shift.

Table 12. *Impact of demand flexibility development WITH demand shift on the market prices' global indicators (compared to the Default cases)*

	2013 scenario			2020 standard scenario			2020 RES+ scenario		
	Default case	MidFlex, FDS *(Variation / default)*	HighFlex, FDS *(Variation / default)*	Default case	MidFlex, FDS *(Variation / default)*	HighFlex, FDS *(Variation / default)*	Default case	MidFlex, FDS *(Variation / default)*	HighFlex, FDS *(Variation / default)*
Average market price (€/MWh)	34.63	33.48 *-3.3%*	33.33 *-3.8%*	47.64	47.30 *-0.7%*	46.75 *-1.9%*	45.46	44.99 *-1.0%*	44.69 *-1.7%*
Average daily spread (€/MWh)	34.03	21.57 *-36.6%*	20.73 *-39.1%*	26.71	24.07 *-9.9%*	22.13 *-17.2%*	43.47	39.31 *-9.6%*	34.11 *-21.5%*

Demand flexibility with demand shift, compared to demand flexibility without demand shift, has a slightly lower impact on the average market prices (between -0.7% and -3.8% compared to -0.9% to -4.3%). This was expected since demand shift increases the prices during low-price hours.

Figure 17. *Average hourly prices in Belgium (2020 standard scenario)*



In addition, for the very same reason demand shift allows decreasing even more the average daily spread, leading to a very significant impact (between -9.6% and -39.1%). Thanks to load shedding combined with demand shift, on average the residual load is flatter, and so are the average prices. This is illustrated by ***Figure 17*** showing the average hourly prices in Belgium within the 2020 standard scenario: not only price peaks are shaved within the HighFlex case, but also price minimums are increased with demand shift (brown curve).

4.4 Quantitative evaluation of demand flexibility development on sustainability

4.4.1 Sustainability global indicators

Table 13 shows the impact of the studied demand flexibility options WITHOUT demand shift on the sustainability global indicators, compared to the Default cases (no demand flexibility), for the three scenarios.

Table 13. *Impact of demand flexibility development WITHOUT demand shift on the sustainability global indicators (compared to the Default cases)*

	2013 scenario			2020 standard scenario			2020 RES+ scenario		
	Default case	MidFlex *(Variation / default)*	HighFlex *(Variation / default)*	Default case	MidFlex *(Variation / default)*	HighFlex *(Variation / default)*	Default case	MidFlex *(Variation / default)*	HighFlex *(Variation / default)*
RES share in total consumption	35.93%	36.01%	36.14%	44.67%	44.82%	45.03%	53.04%	53.16%	53.41%
Total CO_2 emissions (Mt)	1,393	1,383 *-0.7%*	1,372 *-1.5%*	1,049	1,035 *-1.4%*	1,011 *-3.7%*	727	718 *-1.3%*	701 *-3.7%*
Average CO_2 emissions compared to energy generated (t/GWh)	565	563 *-0.4%*	561 *-0.7%*	407	404 *-0.8%*	398 *-2.2%*	282	280 *-0.8%*	276 *-2.4%*

Demand flexibility has an important impact on CO_2 emissions compared to the proportion of load shed. Within our hypotheses, between 10 and 39 million of tons (Mt) of CO_2 would be saved each year. The distribution per country of these savings deserves a detailed analysis (section 4.4.2).

4.4.2 Impact of demand flexibility on CO_2 emissions production per country

Table 14 shows the CO_2 emissions in millions of tons (Mt) per year, for each country within our scope.

The relative impact (in %) of demand flexibility on CO_2 emissions is lower in countries with the highest CO_2 emissions (Germany, Great-Britain, Italy): for example in Germany, between 0.2% and 2.9% of CO_2 emissions would be saved, compared to 4% to 33.9% in France for instance. More surprisingly, the absolute impact (in Mt) is also not very significant in those countries, in particular within the 2013 and 2020 standards scenarios (6 Mt saved in Germany in 2020, compared to 4.4

Mt saved in France). This is clearly related to what we have observed regarding the coal-based production within the different countries (section 4.1.3)[23].

Table 14. *Impact of demand flexibility on CO_2 emissions per country, for the three scenarios (in Mt)*

	2013 scenario			2020 standard scenario			2020 RES+ scenario		
	Default case	MidFlex (Variation / default)	HighFlex (Variation / default)	Default case	MidFlex (Variation / default)	HighFlex (Variation / default)	Default case	MidFlex (Variation / default)	HighFlex (Variation / default)
AT	8.28	8.24 -0.5%	8.22 -0.7%	23.26	23.02 -1.0%	22.37 -3.8%	46.12	45.98 -0.3%	45.84 -0.6%
BE	2.92	2.42 -17.2%	1.89 -35.3%	4.26	4.11 -3.4%	3.80 -10.8%	11.13	10.93 -1.8%	10.39 -6.6%
FR	50.1	48.1 -4.0%	42.2 -15.7%	29.8	27.9 -6.5%	23.5 -21.3%	8.8	8.0 -9.1%	5.8 -33.9%
DE	654	653 -0.2%	651 -0.5%	450	447 -0.8%	441 -2.1%	321	317 -1.3%	312 -2.9%
GB	285	284 -0.1%	284 -0.3%	151	149 -0.9%	146 -3.0%	40	38 -5.1%	35 -12.7%
IT	213	212 -0.9%	211 -1.1%	245	242 -1.4%	239 -2.6%	209	208 -0.4%	205 -2.0%
NL	123	122 -0.4%	121 -1.4%	86	84 -3.2%	81 -6.2%	76	75 -1.1%	73 -3.6%
PT	5.19	4.91 -5.4%	4.37 -15.7%	4.08	3.26 -20.1%	1.35 -66.8%	6.09	6.04 -0.8%	6.02 -1.1%
ES	50.9	48.4 -5.0%	47.8 -6.0%	55.4	54.6 -1.5%	53.1 -4.1%	9.0	8.4 -7.4%	7.7 -14.3%

[23] Apart the impact of demand flexibility on CO_2 emissions, it is worth reminding that within the 2020 RES+ scenario, a very high CO_2 price has been set (40€/t – compared to 10 €/t in the 2020 standard scenario). The important decrease in CO_2 emissions within this scenario is mainly caused by this parameter.

4.4.3 Impact of consumption shift caused by load shedding on sustainability indicators

Table 15 shows the impact of the studied demand flexibility options WITH demand shift on the sustainability global indicators, compared to the Default cases (no demand flexibility), for the three scenarios. It should be compared to *Table 13* which shows these indicators WITHOUT demand shift.

Table 15. *Impact of demand flexibility development WITH demand shift on the sustainability global indicators (compared to the Default cases)*

	2013 scenario			2020 standard scenario			2020 RES+ scenario		
	Default case	MidFlex, FDS *(Variation / default)*	HighFlex, FDS *(Variation / default)*	Default case	MidFlex, FDS *(Variation / default)*	HighFlex, FDS *(Variation / default)*	Default case	MidFlex, FDS *(Variation / default)*	HighFlex, FDS *(Variation / default)*
RES share in total consumption	35.93%	36.09%	36.10%	44.67%	44.77%	44.77%	53.04%	53.08%	53.07%
Total CO_2 emissions (Mt)	1,393	1,388 *-0.4%*	1,386 *-0.5%*	1,049	1,041 *-0.8%*	1,020 *-2.8%*	727	723 *-0.6%*	717 *-1.5%*
Average CO_2 emissions compared to energy generated (t/GWh)	565	564 *-0.3%*	564 *-0.3%*	407	405 *-0.6%*	397 *-2.6%*	282	282 *-0.3%*	280 *-0.9%*

Regarding the share of RES in the total consumption, demand flexibility with demand shift has little impact. Still, compared to demand flexibility with no demand shift, this share is slightly lower, mainly because the total consumption is slightly higher.

Regarding the total CO_2 emissions, the existence of demand shift would not allow the same savings: instead of 10 to 39 million of tons (Mt) of CO_2 saved each year, 5 to 29 Mt would be saved depending on the different cases.

4.5 Quantitative evaluation of demand flexibility development on cross-border market integration

4.5.1 Cross-border market integration global indicators

The following global indicators are monitored to assess the impact of demand flexibility on cross-border market integration:

- The **cross-border energy exchanged** is the sum, over all borders, of the absolute value of the cumulated net cross-border flows over the year. This indicator is a measure of the intensity of cross-border flows during the period studied.
- The **interconnection utilisation score**[24] is the average, over all borders, of the average ratio over all hours between the net cross-border flow and the net transfer capacity (NTC) in the direction of the net flow. It is a measure of the saturation of the existing cross-border infrastructures.
- The **price convergence score**[25] is the average, over all borders, of the proportion of time during which there is no price differential at the border. It is a measure of market integration.
- The **average price differential magnitude** is the average value, over all hours, of the difference between the maximum price reached at a given hour, whatever the corresponding market area is, and the minimum price reached at the same hour. In other words, it is the average hourly spread between the prices of the most expensive and the cheapest markets. It is another measure of market integration, providing a quantification of the extent to which prices are diverging within the studied geographical scope.
- The **total congestion revenue** is the sum, over all hours and all borders, of the hourly net cross-border flow realized at each border multiplied by the price differential at this border.

Table 16 shows the impact of the studied demand flexibility options WITHOUT demand shift on the cross-border market integration global indicators, compared to the Default cases (no demand flexibility), for the three scenarios.

[24] It is expressed as a score out of 100 rather than a percentage, because averaging percentages would not be mathematically correct.
[25] Same comment.

Table 16. *Impact of demand flexibility development WITHOUT demand shift on the cross-border market integration global indicators (compared to the Default cases)*

	2013 scenario			2020 standard scenario			2020 RES+ scenario		
	Default case	MidFlex (Variation / default)	HighFlex (Variation / default)	Default case	MidFlex (Variation / default)	HighFlex (Variation / default)	Default case	MidFlex (Variation / default)	HighFlex (Variation / default)
Cross-border energy exchanged (GWh)	**165,119**	**168,229** 1.9%	**172,063** 4.2%	**223,857**	**230,385** 2.9%	**236,844** 5.8%	**204,678**	**207,474** 1.4%	**209,999** 2.6%
Interconnection utilisation score	**83.5**	**84.2** *0.77%*	**84.9** *1.67%*	**74.2**	**74.7** *0.74%*	**75.6** *1.86%*	**76.7**	**77.2** *0.56%*	**77.5** *1.04%*
Price convergence score	**32.5**	**30.9** *-5.1%*	**29.4** *-9.7%*	**45.6**	**44.5** *-2.5%*	**42.5** *-6.8%*	**44.2**	**43.5** *-1.6%*	**43.0** *-2.8%*
Average price differential magnitude (€/MWh)	**39.48**	**31.55** *-20.1%*	**30.16** *-23.6%*	**41.09**	**39.76** *-3.2%*	**38.53** *-6.2%*	**49.60**	**47.79** *-3.7%*	**47.08** *-5.1%*
Total congestion revenue (M€)	**1,702**	**1,594** *-6.3%*	**1,585** *-6.8%*	**3,831**	**3,792** *-1.0%*	**3,822** *-0.2%*	**5,170**	**5,076** *-1.8%*	**5,044** *-2.4%*

Within the three scenarios, the global cross-border market integration indicators show that:

- Demand flexibility causes a general increase of cross-border flows: the cross-border energy exchanged increases by 1.4% to 5.8%, and the interconnection utilization score increases by 0.56% to 1.86%. This means that cross-border interconnections are used closer to their full capacity (in the relevant market direction).
- The average price differential magnitude drops, in particular within the 2013 scenario. This is related to the previous point, but also to the decrease in the average prices within each market (section 4.3): price peaks being shaved, price differentials between countries are also reduced, on average.
- Still, the price convergence score significantly decreases. This means that even if on average, prices are closer to each other, they are less often equal. This is in fact consistent with the increase of the interconnection utilisation score: when interconnections are fully used, it means that prices are not necessarily equalized.
- The congestion revenue depends on the amount on cross-border flows, and on the price differentials. The increase in cross-border flows being low compared to the decrease in average price differential, the impact of demand flexibility on congestion revenue is negative (in particular within the 2013 scenario). Within our estimates, the decrease in the total congestion revenue would lie between 9 and 126 million euros (representing 0.2% and 6.8% of the total congestion revenue) depending on the cases and the scenarios.

As individual border level, load flexibility has very different impacts which deserve to be studied with care. In addition, demand shift also has a significant impact on the different borders. This is why we present first the global indicators of load flexibility with demand shift (section 4.5.2), and focus on individual borders afterwards (section 4.5.3).

4.5.2 Impact of consumption shift caused by load shedding on cross-border market integration indicators

Table 17 shows the impact of the studied demand flexibility options WITH demand shift on the cross-border market integration global indicators, compared to the Default cases (no demand flexibility), for the three scenarios. It should be compared to *Table 16* which shows these indicators WITHOUT demand shift.

At global level, demand shift has little impact on the total cross-border energy exchanged. Still, we observe that price convergence is negatively impacted by the existence of demand shifts: WITHOUT demand shifts, demand flexibility makes the convergence score drop by 1.6% to 9.7% depending on the different scenarios and cases; WITH demand shift, the price convergence score drops by 1% to 4.7%.

Table 17. *Impact of demand flexibility development WITH demand shift on the cross-border market integration global indicators (compared to the Default cases)*

	2013 scenario			2020 standard scenario			2020 RES+ scenario		
	Default case	**MidFlex, FDS** *(Variation / default)*	**HighFlex, FDS** *(Variation / default)*	**Default case**	**MidFlex, FDS** *(Variation / default)*	**HighFlex, FDS** *(Variation / default)*	**Default case**	**MidFlex, FDS** *(Variation / default)*	**HighFlex, FDS** *(Variation / default)*
Cross-border energy exchanged (GWh)	165,119	169,317 2.5%	171,501 3.9%	223,857	230,509 3.0%	239,705 7.1%	204,678	207,448 1.4%	209,256 2.2%
Interconnection utilization score	83.5	84.1 *0.65%*	83.9 *0.50%*	74.2	74.8 *0.80%*	75.9 *2.33%*	76.7	77.1 *0.45%*	77.0 *0.34%*
Price convergence score	32.5	31.6 *-2.9%*	31.9 *-2.0%*	45.6	44.9 *-1.7%*	43.5 *-4.7%*	44.2	43.8 *-1.0%*	43.9 *-0.9%*
Average price differential magnitude (€/MWh)	39.48	29.63 *-25.0%*	29.54 *-25.2%*	41.09	40.86 *-0.5%*	40.98 *-0.3%*	49.60	48.90 *-1.4%*	47.84 *-3.5%*
Total congestion revenue (M€)	1,702	1,557 *-8.5%*	1,564 *-8.1%*	3,831	3,823 *-0.2%*	3,910 *2.1%*	5,170	5,176 *0.1%*	5,159 *-0.2%*

4.5.3 Impact of load flexibility with and without demand shift on individual borders

Table 18 shows for each border the yearly energy exchanged in TWh. Borders are ranked by alphabetical order; and for a border X-Y, the energy exchanged is positive when at yearly level X exports to Y, and it is negative when Y exports to X.

It can be observed that the impacts on cross-border flows of load flexibility on the one hand, and of demand shift on the other hand, vary a lot for the different borders. In fact, these impacts depend on many factors: notably, the generation mix, the price structure and the level of cross-border capacities of each country influence the way load flexibility (with or without demand shift) impacts cross-border flows. The cross-border impacts are therefore quite complex to analyse. Still, we notice that:

- On some borders, the impact of load flexibility with or without demand shift is low. Borders concerned are: FR-BE, FR-GB, FR-IT_n, FR-CH, GB-ES and IT_n-IT_s. Corresponding rows in *Table 18* are displayed in blue text. Analysis of these borders is carried out in section 4.5.4.
- On other borders, the impact of demand flexibility is significant, and is in general exacerbated by the existence of demand shift. We propose here to study in more details the impacts of demand flexibility on one of them, displayed in red text in ***Table 18***: the France-Spain border. Analysis of this border is carried out in section 0.

Table 18. *Impact of demand flexibility development WITH and WITHOUT demand shift on the energy exchanged per border*

	2013 scenario					2020 standard scenario					2020 RES+ scenario				
Cross-border energy exchanged (TWh)	Default	MidFlex	Midflex FDS	HighFlex	Highflex FDS	Default	MidFlex	Midflex FDS	HighFlex	Highflex FDS	Default	MidFlex	Midflex FDS	HighFlex	Highflex FDS
AT-IT_n	1.37	1.42 *3.2%*	1.35 *-1.9%*	1.47 *6.9%*	1.33 *-2.9%*	-0.37	-0.38 *3.6%*	-0.43 *16.6%*	-0.39 *7.2%*	-0.55 *50.3%*	-0.69	-0.69 *0.6%*	-0.71 *2.8%*	-0.72 *4.9%*	-0.71 *3.5%*
AT-CH	-1.47	-1.43 *-2.9%*	-1.56 *5.8%*	-1.30 *-11.6%*	-1.55 *5.1%*	-4.37	-4.50 *3.0%*	-4.64 *6.2%*	-4.62 *5.6%*	-4.97 *13.8%*	-4.73	-4.78 *0.9%*	-4.73 *-0.1%*	-4.83 *2.1%*	-4.72 *-0.3%*
FR-BE	22.01	22.24 *1.1%*	22.21 *0.9%*	22.33 *1.4%*	22.28 *1.2%*	21.91	22.14 *1.0%*	22.05 *0.6%*	22.30 *1.8%*	22.27 *1.6%*	20.07	20.34 *1.4%*	20.24 *0.9%*	20.66 *3.0%*	20.51 *2.2%*
BE-DE	-	-	-	-	-	-2.67	-2.84 *6.3%*	-3.10 *16.0%*	-3.22 *20.4%*	-3.63 *35.8%*	6.26	6.36 *1.7%*	6.30 *0.8%*	6.36 *1.7%*	6.28 *0.4%*
BE-GB	-	-	-	-	-	1.43	1.55 *8.0%*	1.62 *13.1%*	1.54 *7.5%*	1.98 *38.3%*	2.52	2.59 *2.9%*	2.66 *5.6%*	2.69 *6.7%*	2.89 *14.8%*
BE-NL	-3.16	-3.20 *1.3%*	-3.41 *7.9%*	-3.30 *4.3%*	-3.54 *12.1%*	3.81	4.27 *12.1%*	4.13 *8.4%*	4.38 *15.0%*	4.14 *8.6%*	10.93	11.23 *2.7%*	10.85 *-0.7%*	11.64 *6.4%*	10.68 *-2.3%*
FR-DE	11.24	11.80 *5.0%*	11.62 *3.3%*	12.50 *11.2%*	12.13 *7.9%*	13.84	14.28 *3.2%*	14.20 *2.6%*	14.77 *6.7%*	14.73 *6.4%*	13.12	13.22 *0.7%*	13.16 *0.3%*	13.37 *1.9%*	13.31 *1.4%*
FR-GB	13.17	13.29 *0.9%*	13.38 *1.6%*	13.36 *1.5%*	13.37 *1.5%*	37.00	37.15 *0.4%*	37.06 *0.2%*	37.37 *1.0%*	37.34 *0.9%*	34.11	34.26 *0.5%*	34.26 *0.4%*	34.38 *0.8%*	34.45 *1.0%*
FR-IT_n	16.62	17.04 *2.5%*	16.97 *2.1%*	17.22 *3.6%*	17.05 *2.5%*	25.51	26.42 *3.6%*	26.04 *2.1%*	27.45 *7.6%*	27.25 *6.8%*	23.44	24.12 *2.9%*	23.97 *2.3%*	25.08 *7.0%*	24.77 *5.7%*
FR-ES	-2.77	-2.79 *0.6%*	-3.29 *18.5%*	-2.99 *7.7%*	-3.38 *21.9%*	-7.46	-7.64 *2.3%*	-7.45 *-0.2%*	-7.43 *-0.4%*	-6.72 *-9.9%*	-1.71	-1.75 *2.6%*	-1.68 *-1.7%*	-0.85 *-50.5%*	-1.22 *-28.5%*
FR-CH	24.61	25.01 *1.7%*	24.92 *1.3%*	25.28 *2.7%*	25.23 *2.5%*	29.53	30.32 *2.7%*	30.18 *2.2%*	30.75 *4.1%*	30.54 *3.4%*	29.20	29.77 *1.9%*	29.76 *1.9%*	30.15 *3.2%*	30.08 *3.0%*
DE-NL	10.67	11.06 *3.7%*	11.77 *10.4%*	12.69 *19.0%*	12.73 *19.4%*	13.75	14.99 *9.1%*	15.31 *11.4%*	16.18 *17.7%*	16.99 *23.6%*	-3.86	-3.89 *0.9%*	-3.91 *1.3%*	-3.32 *-13.8%*	-3.45 *-10.6%*
DE-CH	-4.52	-4.22 *-6.6%*	-4.56 *0.8%*	-4.04 *-10.6%*	-4.50 *-0.3%*	-14.16	-14.40 *1.7%*	-14.94 *5.6%*	-14.74 *4.1%*	-16.14 *14.0%*	-18.23	-18.42 *1.1%*	-18.38 *0.8%*	-18.78 *3.0%*	-18.22 *0.0%*
GB-ES	-	-	-	-	-	-7.86	-7.89 *0.3%*	-7.84 *-0.3%*	-7.92 *0.7%*	-7.83 *-0.4%*	-6.35	-6.40 *0.8%*	-6.41 *0.9%*	-6.41 *0.9%*	-6.52 *2.6%*
NL-GB	6.60	6.63 *0.5%*	6.74 *2.0%*	6.66 *0.9%*	6.72 *1.7%*	0.84	0.89 *5.5%*	1.00 *18.7%*	0.87 *3.4%*	1.33 *57.1%*	1.30	1.37 *5.5%*	1.51 *16.4%*	1.50 *16.1%*	1.83 *41.1%*
CH-IT_n	13.62	14.46 *6.2%*	13.86 *1.7%*	15.18 *11.5%*	13.61 *-0.1%*	3.64	4.18 *14.8%*	4.38 *20.3%*	4.61 *26.6%*	5.20 *42.9%*	-2.13	-1.94 *-9.0%*	-2.30 *7.7%*	-2.72 *27.7%*	-3.02 *41.8%*
IT_n-IT_s	24.10	24.47 *1.5%*	24.53 *1.8%*	24.74 *2.7%*	24.76 *2.7%*	29.33	29.64 *1.1%*	29.47 *0.5%*	30.02 *2.4%*	29.96 *2.2%*	23.52	23.72 *0.9%*	23.59 *0.3%*	23.66 *0.6%*	23.50 *-0.1%*
ES-PT	9.17	9.16 *-0.1%*	9.16 *-0.1%*	8.99 *-2.0%*	9.33 *1.7%*	6.36	6.91 *8.7%*	6.67 *5.0%*	8.26 *29.9%*	8.11 *27.6%*	-2.52	-2.61 *3.7%*	-3.02 *19.9%*	-2.88 *14.4%*	-3.07 *22.0%*

4.5.4 Analysis of the impact of load flexibility with and without demand shift on borders FR-BE, FR-GB, FR-IT_n, FR-CH, GB-ES and IT_n-IT_s

In *Table 18* we noticed that demand flexibility (with or without demand shift) had little impact on the energy exchanged at these borders. This can be explained by the very high use of the interconnection capacities at these borders, always in the same direction. *Table 19* shows for each of these borders, and in each direction, the proportion of hours during which the net cross-border flow is higher than 75% and 95% of the interconnection capacity. It appears that at these borders the flows are almost constantly in the same direction, and close to the net transfer capacities. This means that market prices on each side of the borders are in general different. Therefore, the changes in these prices caused by demand flexibility are not high enough to change the general patterns of the flows at those borders.

Table 19. *Interconnection utilization rate and average price differentials on borders FR-BE, FR-GB, FR-IT_n, FR-CH, GB-ES and IT_n-IT_s (default cases)*

		2013 scenario		2020 standard scenario		2020 RES+ scenario	
	Oriented borders	Exports	Imports	Exports	Imports	Exports	Imports
Proportion of hours with net flow greater than 75% of NTC	FR-BE	96%	0%	96%	0%	88%	2%
	FR-GB	98%	1%	91%	0%	85%	1%
	FR-IT_n	95%	0%	91%	1%	86%	4%
	FR-CH	90%	1%	93%	0%	92%	0%
	ES-GB	-	-	92%	2%	82%	10%
	IT_n-IT_s	79%	0%	87%	1%	71%	6%
Proportion of hours with net flow greater than 95% of NTC	FR-BE	91%	0%	95%	0%	86%	2%
	FR-GB	98%	1%	88%	0%	82%	1%
	FR-IT_n	94%	0%	89%	1%	84%	3%
	FR-CH	86%	1%	91%	0%	90%	0%
	ES-GB	-	-	91%	2%	81%	9%
	IT_n-IT_s	71%	0%	83%	1%	64%	5%

4.5.5 Analysis of the impact of load flexibility with and without demand shift on the FR-ES border

With *Figure 18* we illustrate the average impact of load flexibility and demand shift on the hourly production and load in France and in Spain.

Regarding France, one can observe that:

- On average, load shedding occurs mostly between 8am and 1pm in the morning, and between 6pm and 8pm in the evening (bottom part of the top left hand graph). When demand shift applies, it is positioned in general at night (between 10pm and 5am).
- The average variation in the French production follows the same pattern, but with a lower magnitude: in the HighFlex case, load sheds on average by 1,500 MW (750 MW in the MidFlex case); the corresponding decrease in the French production is 1,000-1,200 MW in the HighFlex case (300-400 MW in the MidFlex case). The same can be observed for the

magnitude of demand shift: where 1,200 MW are shifted to off-peak hours in the HighFlex case (600 MW in the MidFlex case), the production increase by 800 MW only (400 MW in the MidFlex case). This shows that load shedding and demand shifts are partially addressed by the domestic production, the rest being addressed by an adaption of cross-border flows. Therefore, load shedding and demand shift in France may impact the production in all countries the French market is coupled with.

Regarding Spain, we observe that:

- There is a lower difference, compared to France, in the magnitude of the variation in domestic load on the one hand, and in domestic production on the other hand, except for the load shedding peak which occurs on average between 8pm and 9pm. We interpret this lower difference as a consequence of the lower interconnection capacities of Spain compared to France: within “electric peninsulas” (with limited interconnection capacities) load shedding and demand shifts must be compensated mainly with an adaptation of the domestic production.
- The peak load in Spain is in general later in the day than the peak load in France. Therefore, when the Spanish price peak is shaved (in general between 8pm and 9pm), Spain can increase its exports towards France where load is more rarely shed at this hour (net cross-border flow represented in Figure *19*).

Figure 18. *Average hourly variation in load and production in France and in Spain, when load flexibility and demand shift apply (2013 scenario)*

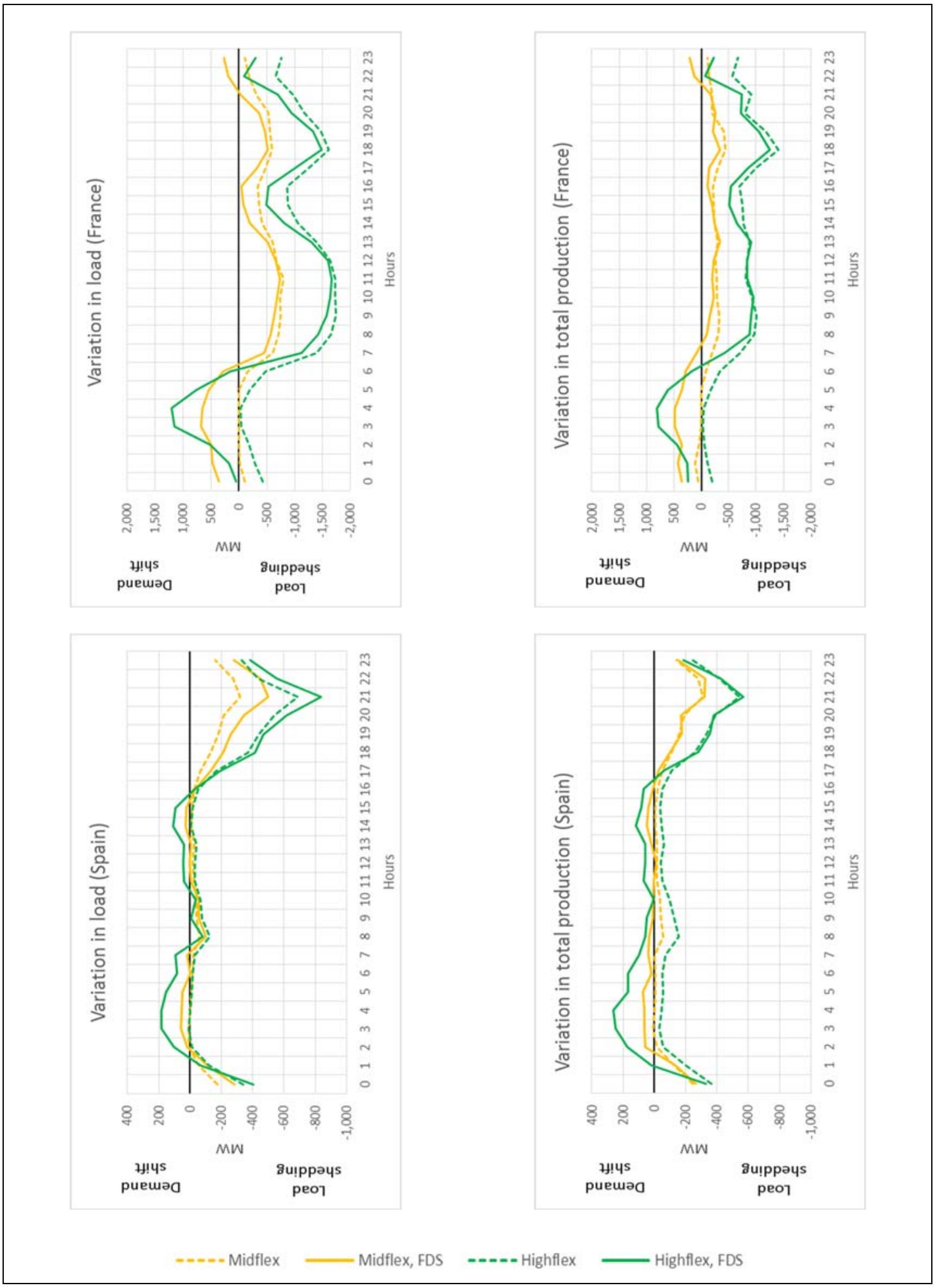
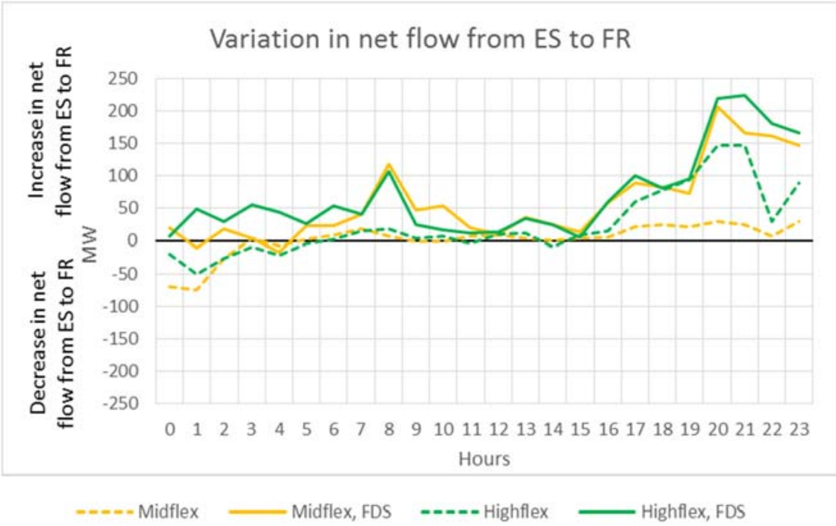


Figure 19. *Average hourly variation in cross-border flow between Spain and France, when load flexibility and demand shift apply (2013 scenario)*



5 CONCLUSIONS

In order to achieve European Union energy policy and decarbonisation targets, demand flexibility can be a key component. Quantifying the benefits of demand flexibility is however very challenging and complex, since the needs and the interconnection of energy systems are very heterogeneous throughout Europe. Indeed, consumers' habits and density, level of industrialization, generation mix and geographic structure are all factors that make this assessment complex.

Various studies have investigated possible impacts of the demand flexibility (see references [6] to [13]). We propose in this report a complementary approach based on the OPTIMATE tool, which allowed us to achieve an extensive study on the possible impacts on short-term market outcomes of the development of demand flexibility. With this Market4RES report, we propose an original and transparent way to quantify the benefits of demand flexibility. The outcomes of the analyses performed have been structured along five families of indicators: generation mix, costs and profits, market prices, sustainability, and cross-border market integration.

Furthermore, demand response can be related to either shifting electricity demand from periods of high prices to periods of lower prices, or to reducing electricity consumption in periods of high prices (with no consumption shifting). In the present study, it has been decided to consider two extreme situations: on the one hand, no demand shift is associated to load shedding; on the other hand, full demand shift occurs (meaning that no global energy savings occur). These two extreme variants represent boundaries of the possible impacts of a realistic situation in terms of demand response behaviour. In further studies, it could be possible to model a mixed situation (for example 50% of demand shift); it could also be possible to combine demand flexibility development with other market design aspects such as renewable support schemes. Still, carrying out such studies being very complex, not all possibilities could have be included in the work performed within the framework of the Market4RES project. Also, studying the impacts of demand response on a restricted geographical scope but including the modelling of local network constraints and of shorter-term markets (intraday, balancing) could be the purpose of future studies to be done with the OPTIMATE tool.

Demand flexibility can be one way to address many issues such like sustainability challenges or cross-border market integration. Concerning sustainability, demand flexibility has an important impact on CO_2 emissions compared to the proportion of load shed. Within our hypotheses, between 10 and 39 million of tons (Mt) of CO_2 would be saved each year, representing 0.7% to 3.7% of the total CO_2 emissions from power generation. Furthermore, the existence of demand shift would allow lower savings, from 5 to 29 Mt depending on the different scenarios cases studied. Regarding cross-border market integration, one of the main impact of demand flexibility is a general increase of cross-border flows, and of the interconnection utilization rate, helping to optimize the utilization of grid infrastructure.

This report outlines many impacts of demand flexibility. It is now legitimate to ask what the policy recommendations following these studies can be. Elements to answer this fundamental question will be addressed in upcoming Market4RES reports under the work package 6 of the project "Conclusions, Recommendations & Procedure Guidelines".

6 REFERENCES

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