"Innovative Business Models for Market Uptake of Renewable Electricity unlocking the potential for flexibility in the Industrial Electricity Use"

Quantifying the Economic Benefits of Flexible Industrial Demand

Deliverable 5.1
May 2017

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This report has been produced by Dimitrios Papadaskalopoulos, Roberto Moreira, Danny Pudjianto, Predrag Djapic, Fei Teng, and Goran Strbac from Imperial College London. The authors thankfully acknowledge the valuable contributions from all project partners.

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Table of Contents

Executive Summary

Scope of deliverable

The scope of this deliverable report lies in summarizing the work carried out in Tasks 5.1 and 5.2 of the IndustRE project, which quantify the economic benefits that flexible industrial demand (FID) can bring in the European context. More specifically:

- ***Task 5.1 – Top-down quantification of economic benefits***: focuses on quantifying the economic benefits from the perspective of the whole power system (i.e. the societal perspective). In other words, Task 5.1 aims at quantifying the savings in capital and operating costs associated with the development and operation of the European power system brought by the integration of flexibility in industrial demand.
- ***Task 5.2 – Bottom-up quantification of economic benefits***: focuses on quantifying the economic benefits from the perspective of a single flexible industrial consumer. In other words, Task 5.2 aims at quantifying the cost savings an industrial consumer can achieve by deploying flexibility in its operation.

Role of industrial demand flexibility in the emerging European power system

Driven by environmental and energy security concerns, the European power system is facing the challenge of decarbonization. However, the majority of low-carbon generation sources are characterized by inherent variability, intermittency and non-controllability, creating significant challenges in system balancing and resulting in efficiency losses for conventional generation and / or curtailment of renewable generation. Furthermore, the decarbonization of transport and heat demand is expected to increase demand peaks dramatically, leading to significant investments in new, under-utilised generation and network capacity. In this setting, industrial demand flexibility has the potential to enable a more cost-effective transition to a low-carbon future, by supporting system balancing and limiting peak demand levels.

Representation of industrial demand flexibility

This flexibility refers to the ability of industrial consumers to modify their electricity consumption patterns. It should be stressed that such modifications do not generally involve reduction / increase of the overall electricity consumption, but rather shift / redistribution of electricity consumption across time, as most industrial consumers need certain levels of energy for carrying out their respective processes. This means that their overall electricity consumption during certain temporal horizons (e.g. a day) cannot significantly change, but the specific time periods that electricity is acquired within such horizons can be flexibly modulated. This entails that the performance of industrial activities will not be affected.

Since the flexibility of different industrial plants varies greatly according to their specific industrial activity, technical installations and production process as well as the perceptions, preferences and requirements of their owners and operators, the authors have employed a generic, process-agnostic model for the representation of industrial demand flexibility. According to this model, the electricity demand of an industrial consumer at any hour can be reduced / increased with respect to the baseline level within a proportional limit a ($0 \leq a \leq 100\%$) as long as the total size of demand reductions is equal to the total size of demand increases within the horizon of a day. For example, $a = 0\%$ implies that industrial demand does not exhibit any time-shifting flexibility, while $a = 100\%$ implies that the whole industrial demand can be shifted in time.

Top-down quantification of economic benefits of industrial demand flexibility

Flexible industrial demand has potential impacts on multiple sectors of the European power system (generation, transmission and distribution) across multiple time horizons (long-term planning, short-term scheduling and real-time balancing). As a result, the comprehensive quantification of FID benefits for the whole power system is a complex task that requires advanced modelling approaches to capture different layers of the power system operation and development. Based on the extensive experience of the Imperial College partners in whole-system value assessment of different technologies, the following modelling strategies have been adopted:

- ***Separate assessment for European generation / transmission level and target countries' local distribution level***: European countries are already interconnected through high-voltage interconnection links and interconnection projects are expected to increase. On the other hand, the planning and operation of distribution networks are highly local tasks, as these networks are not interconnected and need to deal with local demand and generation conditions. For this reason, two different modelling approaches are employed for the assessment of the economic benefits of FID. The first one (involving the Whole-electricity System Investment Model - WeSIM and the Stochastic Unit Commitment Model - SUCM) deals with the assessment of the generation- and transmission-related benefits at the European level, by incorporating an integrated model of the interconnected European transmission network. The second one (Distribution Network Planning Model - DistPlan) deals with the assessment of the distribution-related benefits in each of the 6 target countries of IndustRE separately (Belgium, France, Germany, Italy, Spain and UK). Given that the size and diversity of distribution networks is very large and very limited data is publicly available regarding the actual topology and technical characteristics of real distribution networks, this model is based on analysing a limited number of statistically representative networks rather than actual networks.

- ***Comprehensive assessment of long-term investment and short-term operation benefits***: The increased penetration of renewable generation in the European system is expected to significantly complicate system operation and enhance the volume of required balancing services i.e. services required for the secure operation of the system, such as reserves and frequency response. In this context, the accurate assessment of the benefits of FID requires advanced system operation models capable of capturing the inherent uncertainty of renewable generation through suitable stochastic techniques. Furthermore, system operation is naturally coupled with investment decisions given that the available generation and network assets need to ensure the secure and economic operation of the system. However, given the high modelling and computational complexity of such stochastic techniques, their incorporation in a European-wide generation and transmission model that would simultaneously optimize long-term investment decisions and stochastic short-term operation, is computationally challenging. For these reasons, a two-stage approach has been employed to quantify the overall economic benefits of FID at the European generation / transmission level. The WeSIM model determines optimal (least-cost) generation and transmission investment and operation decisions at the whole European level, by employing however a simplified deterministic representation of system operation not capturing uncertainty factors. The investment decisions of the WeSIM model are then inputted to the SUCM model which refines operation decisions by capturing uncertainty factors through advanced stochastic modelling and optimization techniques.

The modeling horizon for the top-down quantification of FID economic benefits is 2030. In other words, the deployed models use projections of demand and renewable generation levels on 2030 and optimize investment and operation decisions to minimize the system costs required to satisfy these projections. Considering that the baseline expectation of the European Commission is that renewable generation will cover around 45% of the overall electricity consumption in Europe is 2030, two alternative scenarios involving 30% and 60% of the overall electricity consumption to be supplied by renewable generation (expressing a pessimistic and optimistic pathway for the integration of renewable generation in Europe respectively), are investigated in this report.

Figure ES1 presents the generation and transmission cost savings (in billion Euros per year) brought by different levels of industrial demand flexibility (with respect to the benchmark scenario $a = 0\%$ which corresponds to a case without any industrial demand flexibility) and the two alternative scenarios regarding the level of renewable generation in 2030. The three different colours on each column represent different streams of cost savings brought by FID:

- ***G CAPEX*** (denoted in blue colour): savings in capital costs brought by avoiding investments in additional generation capacity.
- ***T/I CAPEX*** (denoted in red colour): savings in capital costs brought by avoiding investments in additional transmission and interconnection capacity.
- ***OPEX*** (denoted in green colour): savings in operational costs brought by enabling higher energy production by renewable and low-cost generation sources and

providing balancing services (thus reducing the efficiency losses of conventional generators).

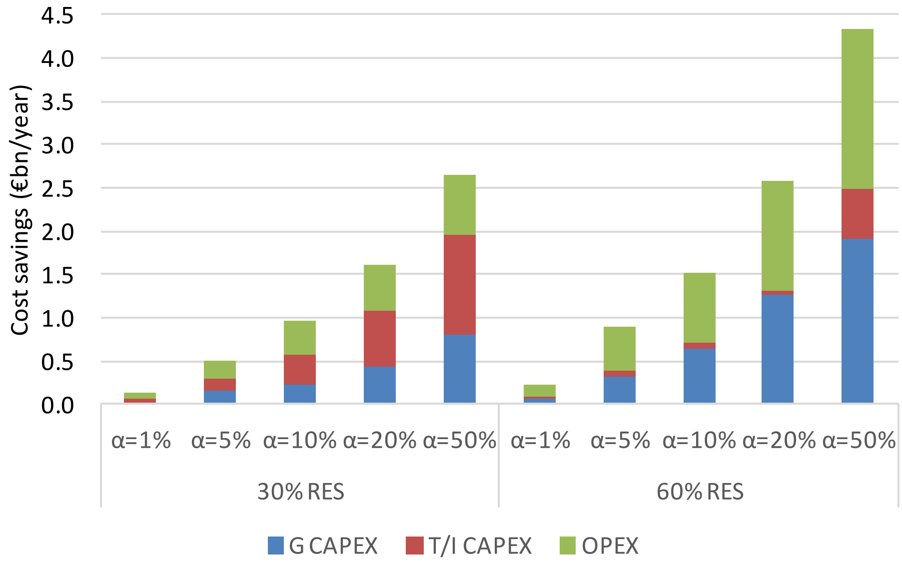

Figure ES1: *European electricity generation and transmission cost savings brought by FID for different scenarios of industrial demand flexibility and renewable generation.*

As expected, higher levels of industrial demand flexibility (higher values of a) enhance the different streams of cost savings and increase the total cost savings, for both renewable generation scenarios. Furthermore, it is observed that the total cost savings are higher for a higher penetration of renewable generation, since system balancing becomes more challenging and the flexibility requirements are increased. This trend demonstrates the synergy between increased penetration of renewable generation and industrial demand flexibility, which constitutes a fundamental result of the IndustRE project.

Figure ES2 presents the capital cost savings in distribution network reinforcements (in million Euros per year) brought by different levels of industrial demand flexibility (with respect to the benchmark scenario $a = 0\%$). These savings are driven by the beneficiary impact of industrial demand flexibility in reducing peak demand levels. As expected, higher levels of industrial demand flexibility (higher values of a) increase these cost savings.

It is observed however that these savings vary significantly among the 6 target countries of the project. This variation is driven by the following factors:

- Distribution network reinforcements are driven by peak demand levels. As a result, countries with an expected high demand growth towards 2030 exhibit high stress on their distribution networks, which cannot be easily relieved by industrial demand flexibility.
- The value of industrial demand flexibility in reducing peak demand levels depends on the share of industrial demand over the total demand in each country. In other

words, a particular value of industrial demand flexibility a is translated in a higher peak demand reduction potential in countries with a higher share of industrial demand and a lower potential in countries with a lower share of industrial demand.

- The costs of distribution network reinforcements and consequently the value of industrial demand flexibility in reducing them depends on the size of the distribution network which is obviously correlated with the size of the country.

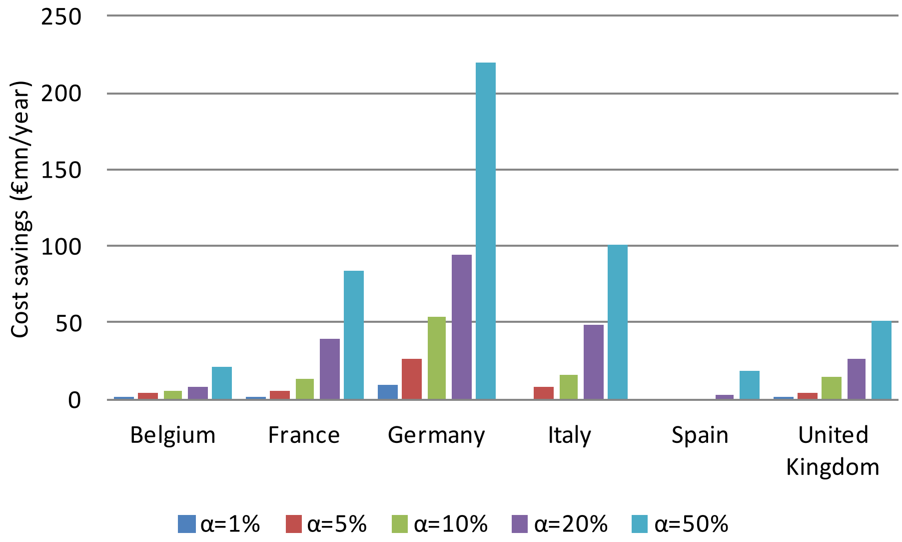

Figure ES2: *Electricity distribution cost savings brought by FID in the 6 target countries of IndustRE for different scenarios of industrial demand flexibility.*

Bottom-up quantification of economic benefits of industrial demand flexibility

Under a suitable market and regulatory framework, part of the above system cost savings should be transferred to the flexible industrial consumers in order to remunerate them for the flexibility they provide to the system and encourage further flexibility provisions. In order to quantify these cost savings of flexible industrial consumers, the Imperial College partners have developed a new model, referred to as Bottom-Up Quantification Model (BUQM). This model represents the perspective of a single industrial consumer, which aims at minimizing its total electricity cost by making optimal use of its flexibility in energy, balancing and generation / transmission / distribution capacity markets. By simultaneously considering energy, balancing and capacity value streams, the BUQM model inherently accounts for interdependencies and conflicts between the provisions of different services by the flexible industrial consumer. The model optimizes the allocation of the consumer’s flexibility among conflicting services, given the market prices associated with these services.

The outcomes of this bottom-up quantification of FID benefits depends to a great extent on the electricity market framework, involving a) the market rules associated with the participation of different entities in energy, balancing and capacity markets and b) the pricing mechanisms associated with energy, balancing and capacity products. The objective of Task 5.2 of the IndustRE project is the quantification of the cost savings of a flexible industrial consumer under an “ideal” electricity market framework, which involves cost-reflective pricing mechanisms, does not impose excessive constraints on the potential market participants and is uniform across the different European countries. Although the development of such an “ideal” market framework is an extremely challenging task, the authors of this deliverable report have made a number of assumptions regarding certain aspects of a suitable framework, which they believe are in line with the main conclusions of relevant research, industrial and policy activities in Europe. The main assumptions are: a) in order to ensure cost-reflective energy, balancing and capacity market prices, these prices are determined based on the outcomes of the European power system optimization performed by Task 5.1, b) in order to enhance the cost-efficiency of the European power system, a single, coupled European-wide market is assumed for energy, balancing services, generation capacity and transmission capacity services and c) limitation and practical constraints imposed by current market regulation on the participation of industrial consumers in the electricity markets are neglected.

The industrial consumer examined in the studies is characterized by a yearly demand profile corresponding to an actual typical industrial site in Europe with a peak demand of 2666 kW. A number of different scenarios are investigated concerning:

- *The extent of flexibility characterizing the examined industrial consumer*: This is expressed by the parameter α_c in order to differentiate it from the extent of flexibility characterizing the rest of the industrial demand in the European system.
- *The extent of flexibility characterizing the rest of the industrial demand in the system (other than the examined consumer)*: This is expressed by the parameter α_s in order to differentiate it from the extent of flexibility characterizing the examined industrial consumer.
- *The level of renewable generation penetration in the European system*: Two alternative scenarios are examined, involving 30% and 60% of the overall electricity consumption in Europe to be supplied by renewable generation.
- *The country in which the examined industrial consumer is located*: Six alternative scenarios are investigated in each of which the examined consumer is located in each of the 6 target countries of the project (Belgium, France, Germany, Italy, Spain and UK).

Figure ES3 presents the cost savings (with respect to the benchmark scenario $a\_c = 0\%$) achieved by the examined consumer for a scenario with 60% RES, $a\_s = 10\%$ and different scenarios regarding the examined consumer’s flexibility and location. As expected, higher levels of flexibility (higher values of a_c) increase the total cost savings for the examined consumer, since they enhance its position in energy, balancing and capacity markets.

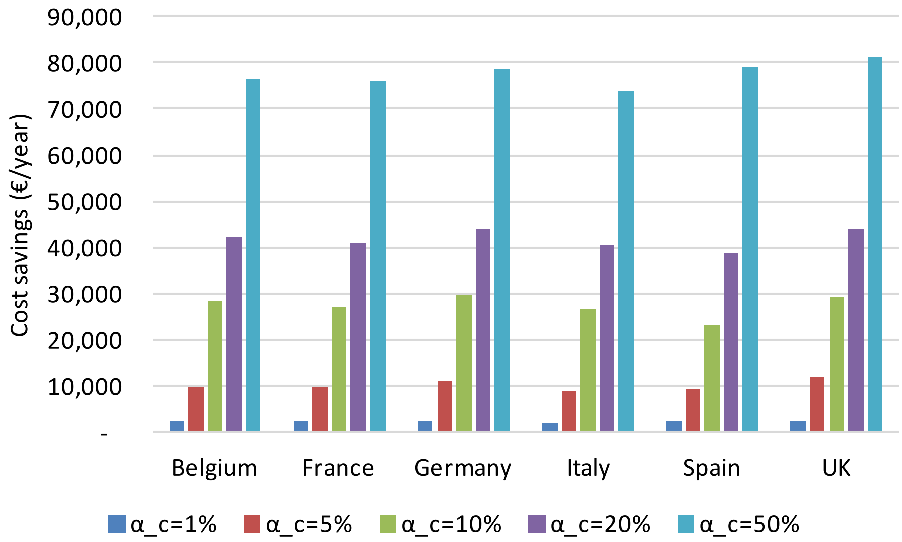

Figure ES3: *Total cost savings achieved by the examined industrial consumer for a scenario with 60% RES,* $a\_s = 10\%$ *and different scenarios regarding its extent of flexibility and its location.*

Figure ES4 presents the cost savings (with respect to the benchmark scenario $a\_c = 0\%$) for a scenario with 60% RES, $a\_c = 10\%$ and different scenarios regarding the flexibility characterizing the rest of the industrial demand in the system and the location of the examined consumer. The cost savings achieved by the examined consumer are reduced as the flexibility of other industrial consumers in the system is increased, since the examined consumer faces increased competition in the energy, balancing and capacity markets.

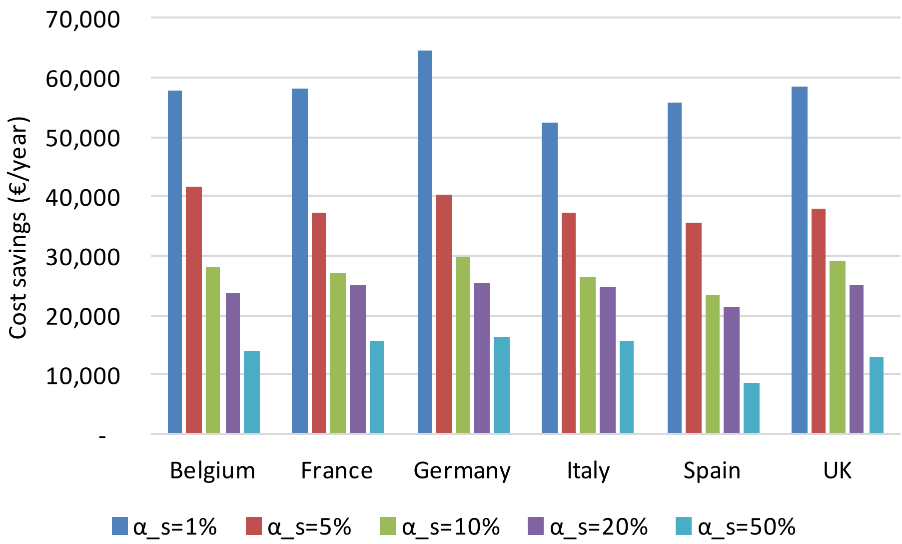

Figure ES4: *Total cost savings achieved by the examined industrial consumer for a scenario with 60% RES,* $a\_c = 10\%$ *and different scenarios regarding its location and the extent of flexibility characterizing the rest of the industrial demand in the system.*

1. Introduction

1.1 Scope of deliverable

The scope of this deliverable report lies in summarizing the work carried out in Tasks 5.1 and 5.2 of the IndustRE project. The objective of these two tasks is essentially the quantification of the economic benefits that flexible industrial demand (FID) can bring in the European context. More specifically:

- ***Task 5.1*** focuses on quantifying the economic benefits from the perspective of the whole power system (i.e. the societal perspective). In other words, Task 5.1 aims at quantifying the savings in capital and operating costs associated with the development and operation of the European power system brought by the integration of flexibility in industrial demand. This task will be referred to as *top-down quantification of FID economic benefits* in the remainder of this report.
- ***Task 5.2*** focuses on quantifying the economic benefits from the perspective of a single flexible industrial consumer. In other words, Task 5.2 aims at quantifying the cost savings an industrial consumer can achieve by deploying flexibility in its operation. This task will be referred to as *bottom-up quantification of FID economic benefits* in the remainder of this report.

In order to achieve the above objectives, dedicated optimization models have been developed by the Imperial College partners. Technical and economic data required for the analysis have been obtained from various public sources and have been inputted to the developed models. In order to perform a comprehensive analysis, different scenarios have been examined regarding: a) *the extent of industrial demand flexibility*, expressed as the % of industrial electricity consumption that can be flexibly shifted / redistributed across time, and b) *the level of renewable generation penetration in the European power system*, expressed as the % ratio of the European electricity consumption that is supplied by renewable generation sources.

1.2 Structure of deliverable

The rest of this deliverable is organized as follows:

- **Chapter 2** briefly discusses the emerging challenges for the European power system driven by the envisaged decarbonization of the energy sector and identifies on a theoretical basis the economic benefits that FID can bring in this context.
- **Chapter 3** outlines the modelling approaches employed in IndustRE in order to quantify these benefits.
- **Chapter 4** presents the examined studies, the employed data and the obtained results regarding the top-down quantification of FID economic benefits.

- **Chapter 5** presents the examined studies, the employed data and the obtained results regarding the bottom-up quantification of FID economic benefits.

2. Emerging challenges for the European power system and the role of industrial demand flexibility

2.1 Emerging challenges for the European power system

Electrical power systems in Europe and beyond are currently undergoing fundamental changes, mainly driven by environmental and energy security concerns. The continuously increasing levels of greenhouse gas emissions in the atmosphere have raised serious environmental and climate change concerns. In response to such concerns, the European Commission has set legally binding targets to achieve 20% reduction in greenhouse gas emissions by 2020 (with respect to the 1990 baseline levels) [1], extended to a further ambitious target of 40% reduction by 2030 [2]. Apart from the issue of climate change, growing energy security concerns emerge over the dependency of electricity generation on fossil fuels exhibiting a continuously reducing availability and a subsequent increase of their prices.

In the context of addressing the above environmental and energy security concerns, both energy generation and demand are facing the challenge of decarbonisation. Regarding the former, decarbonisation of electricity generation is already under way through the wide deployment of renewable and low-carbon generation sources. The European Commission has put forward a legally binding target for renewable energy sources to cover 20% of the total energy consumption in the European Union by 2020 [1], extended to a further target of 27% by 2030 [2]. However, the majority of those sources -especially wind and solar generation which constitute the dominant renewable energy technologies in Europe- are characterized by inherent variability, intermittency and non-controllability. Their power output is not only extremely variable, but is also zero during periods of low wind speed or no sunshine.

Given that demand is currently treated as an inflexible, uncontrollable load, the required flexibility for balancing the system and offering the required ancillary services is solely provided by conventional generators. In a future characterised by an increased penetration of renewable generation, these conventional generation units will be producing much less energy, as absorption of the low-cost and CO2-free production of renewable generators will be prioritised in the merit order. However, given that this renewable generation is variable and intermittent, the conventional generators need to remain in the system and operate part-loaded as a back-up energy source (e.g. operating in periods of low wind speed) and flexibility provider, since renewable generators not only have very limited capabilities to provide system balancing services, but they are also making system balancing more challenging. This under-utilisation of conventional generation assets implies that the cost efficiency of their operation will reduce. Furthermore, in cases where the flexibility of the conventional generation fleet is not sufficient, the last resort for system balancing lies in curtailing renewable generation. This means that due to balancing challenges, renewable generation assets with high capital costs are also under-utilised and thus may not achieve their CO2 emissions reduction potential.

At the demand side, significant decarbonisation of the transport and heat sectors is expected beyond 2030. Traditional technologies for the satisfaction of transportation and heating consumers' requirements (internal combustion engines for transportation and gas / oil fired technologies for heating) are based on the intense consumption of fossil fuels and the emission of a significant portion of the total greenhouse gases [3]. In combination with the ongoing and future decarbonisation of electricity generation systems, strong motives arise for the electrification of those technologies. Recent technological developments in the automotive and heating systems' sectors have techno-economically enabled this transition with the production and efficient operation of *electric vehicles* (EV) [4] and *electric heat pumps* (EHP) [5] respectively. Nevertheless, due to the natural energy intensity of transportation vehicles and heating loads, the environmental and energy security potential of this transition is accompanied by the introduction of a considerable amount of new demand in power systems. Going further, due to the temporal patterns of vehicles' and heating systems' use by the consumers, the new demand peaks are disproportionately higher than the increase in the total electrical energy consumption [6].

Given that demand is currently treated as an inflexible, uncontrollable load, the demand peaks are satisfied by building sufficient generation and network capacity (given certain security margins). The disproportional increase in demand peaks with respect to the increase in overall energy consumption, induced by the envisaged electrification of transport and heat sectors, means that a significant amount of new generation and network capacity needs to be built in the coming years, and this capacity will be significantly under-utilised as it will be used only to cover the increased demand peaks.

The above factors imply that future power systems will be characterized by under-utilized assets and high capital and operating costs.

2.2 Role of industrial demand flexibility in emerging context

During the last years, the role and value of demand flexibility in addressing the above system challenges has attracted significant interest by the European Commission, governments, industry and academia. This project focuses specifically on the significant flexibility potential of industrial demand. This flexibility refers to the ability of industrial consumers to modify their electricity consumption patterns. It should be stressed that such modifications do not generally involve reduction / increase of the overall electricity consumption, but rather shift / redistribution of electricity consumption across time, as most industrial consumers need certain levels of energy for carrying out their respective processes. This means that their overall electricity consumption during certain temporal horizons (e.g. day or week) cannot significantly change, but the specific time periods that electricity is acquired within such horizons can be flexibly modulated. In other words, load reduction during certain periods is accompanied by a *load recovery effect* during preceding or succeeding periods.

Suitable coordination of such industrial demand flexibility has the potential to:

- *Support system balancing* in a future with an increased penetration of renewable generation and therefore reduce the curtailment of renewable generation and the efficiency losses of conventional generation, and
- *Limit peak demand levels* and therefore avoid capital intensive investments in under-utilized generation and network assets.

In other words, FID has the potential to reverse the trend of asset under-utilization and enable a more cost-effective transition to a low-carbon future. Under a suitable market and regulatory framework, part of these system cost savings will be transferred to the industrial consumers through a reduction of their electricity costs. The top-down and bottom-up assessments of FID benefits investigated in this report aim at quantifying these system cost savings and industrial consumers' cost savings, respectively.

3. Modelling approaches for quantifying the benefits of FID

This chapter outlines the analytical modelling approaches employed in IndustRE for the quantification of FID benefits. The first modelling requirement for achieving this objective lies in the representation of the flexibility of industrial demand, which is presented in Section 3.1. This FID model is then incorporated in modelling frameworks dedicated to the top-down (Task 5.1) and bottom-up (Task 5.2) quantification of FID benefits, which are presented in Sections 3.2 and 3.3 respectively.

3.1 Representation of industrial demand flexibility

As discussed in Section 2.2, industrial demand flexibility refers to the ability of industrial consumers to modify their electricity consumption patterns. Modelling of such flexibility obviously constitutes a fundamental step for the quantification of FID benefits. As discussed in the previous IndustRE deliverables D3.2 [7] and D3.3 [8] however, the flexibility of different industrial plants varies greatly according to their specific industrial activity, technical installations and production process as well as the perceptions, preferences and requirements of their owners and operators. The development of a detailed flexibility model accurately capturing all these factors for different types of industrial plants is a very complex and time consuming process. Furthermore, the incorporation of such complicated installation and process models in the already complex system and market models required for a comprehensive quantification of FID economic benefits (detailed in Sections 3.2 and 3.3) is subject to tractability limitations.

For these reasons, the IndustRE consortium has decided to employ a generic, process-agnostic model for the representation of industrial demand flexibility. According to this model, the electricity demand of an industrial consumer at each hour can be reduced / increased with certain limits, as long as the total size of demand reductions is equal to the total size of demand increases within the horizon of a day. As discussed in Section 2.2, the latter constraint is imposed since industrial consumers need certain levels of energy for carrying out their respective processes. In other words, load reduction during certain hours is accompanied by a *load recovery effect* during preceding or succeeding hours.

This generic flexibility model is analytically expressed through equations (1) and (2) below, where d_t^{base} expresses the baseline industrial power demand at hour t (i.e. the power that would normally be consumed if flexibility was not deployed), d_t^{flex} expresses the industrial power demand at hour t if flexibility is deployed and T^s represents the set of hours including the first hour of each day.

$$(1-a) * d_t^{base} \leq d_t^{flex} \leq (1+a) * d_t^{base}, \forall t \quad (1)$$

$$\sum_t^{t+23} d_t^{base} = \sum_t^{t+23} d_t^{flex}, \forall t \in T^s \quad (2)$$

Constraint (1) expresses the limits of demand change at each period due to the deployment of demand flexibility as a ratio a $(0 \leq a \leq 100\%)$ of the baseline demand; for example, $a = 0\%$ implies that industrial demand does not exhibit any time-shifting flexibility, while $a = 100\%$ implies that the whole industrial demand can be shifted across time. Constraint (2) ensures that the industrial demand redistribution is energy neutral within a daily horizon i.e. the total size of demand reductions is equal to the total size of demand increases within the horizon of a day.

Since the extent of industrial demand flexibility, expressed by the ratio a, can vary greatly according to the specific industrial activities, technical installations and production processes of different industrial plants, as well as the perceptions, preferences and requirements of their owners and operators, different scenarios have been examined, including both low and high extremes; specifically, the examined scenarios include the values $a = 1\%$, $a = 5\%$, $a = 10\%$, $a = 20\%$, and $a = 50\%$, along with the benchmark scenario $a = 0\%$ which corresponds to a case without any industrial demand flexibility.

It should be noted that the practical deployment of industrial demand flexibility may be subject to certain costs. These could include fixed capital costs, associated with metering, communication and control equipment enabling the modification of electricity consumption patterns, as well as variable operating costs, expressing the costs incurred by modifications in the industrial process and depending on the extent to which the electricity consumption pattern is modified. As with the extent of industrial demand flexibility, these costs are expected to vary greatly across different industrial consumers. The investigation and analysis of such costs has been set out of the scope of the IndustRE project, which focuses on quantifying solely the economic benefits of industrial demand flexibility. However, we envisage that these economic benefits can serve as a benchmark for a future comparison with the associated costs, and thus the establishment of a comprehensive business case for the realization of industrial demand flexibility.

3.2 Top-down quantification of FID benefits

Based on the discussion in Chapter 2, FID can have beneficial impacts across multiple time horizons, including:

- *Long-term planning horizon* (years before energy delivery), since FID can avoid investments in generation and network assets that are planned years before their actual utilization for the delivery of energy.
- *Short-term scheduling horizon* (days or hours before energy delivery), since FID enables higher energy production by renewable and low-cost generation sources.
- *Real-time balancing horizon* (seconds before energy delivery), since FID can provide reserve and frequency response services, reducing the efficiency losses of conventional generators and the curtailment of renewable generation.

Furthermore, FID can have beneficial impacts across multiple sectors of the power system, including:

- *Generation system*, since FID can avoid investments in additional generation capacity and improve the operational efficiency of existing generation units.
- *Transmission network*, since FID can avoid investments in additional transmission (high-voltage) network capacity.
- *Distribution network*, since FID can avoid investments in additional distribution (low-voltage) network capacity.

It therefore becomes evident that the comprehensive quantification of FID benefits for the whole power system is a complex task that requires advanced modelling approaches. The consideration of multiple timescales and multiple sectors, each characterized by its own technical and economic peculiarities, makes it practically impossible to quantify the whole system benefits through a single analytical model. Different modelling approaches are required to capture different layers of the power system operation and development. Based on the extensive experience of the Imperial College partners in whole-system value assessment of different technologies, the following modelling strategies have been adopted:

- ***Separate assessment for European generation / transmission level and target countries' local distribution level***: European countries are already interconnected through high-voltage interconnection links. Furthermore, interconnection projects are expected to increase due to the benefits of exploiting the natural diversity of different renewable generation technologies in different countries and the enhancement of the competitiveness of the electricity market. On the other hand, the planning and operation of distribution networks are highly local tasks, as these networks are not interconnected and need to deal with local demand and generation conditions. For this reason, two different modelling approaches are employed for the assessment of the economic benefits of FID. The first one (involving the models WeSIM and SUCM, detailed in Sections 3.2.1 and 3.2.2 respectively) deals with the assessment of the generation- and transmission-related benefits at the European level, by incorporating an integrated model of the interconnected European transmission network. The second one (DistPlan, detailed in Section 3.2.3) deals with the assessment of the distribution-related benefits in each of the 6 target countries of IndustRE separately (Belgium, France, Germany, Italy, Spain and UK), by incorporating detailed models of the distribution networks in these countries.

- ***Comprehensive assessment of long-term investment and short-term operation benefits***: The increased penetration of renewable generation in the European system is expected to significantly complicate system operation and enhance the volume of required balancing services i.e. services required for the secure operation of the system, such as reserves and frequency response. In this context, the accurate assessment of the benefits of FID requires advanced system operation models capable of capturing the inherent uncertainty of renewable generation through suitable stochastic techniques. Furthermore, system operation is naturally coupled with investment decisions given that the available generation and network assets need to ensure the secure and economic operation of the system. However, given the high modelling and computational complexity of such stochastic techniques, their incorporation in a European-wide generation and transmission model that would simultaneously optimize long-term investment decisions and stochastic short-term operation, is computationally challenging. For these reasons, a two-stage approach has been employed to quantify the overall economic benefits of FID at the European generation / transmission level. The WeSIM model (detailed in Section 3.2.1) determines optimal generation and transmission investment and operation decisions at the whole European level, by employing however a simplified deterministic representation of system operation not capturing uncertainty factors. The investment decisions of the WeSIM model are then inputted to the SUCM model (detailed in Section 3.2.2) which refines operation decisions by capturing uncertainty factors through advanced stochastic modelling and optimization techniques.

3.2.1 Whole-Electricity System Investment Model (WeSIM)

The *whole-electricity system model* (WeSIM) [9] is a holistic optimisation model of the interconnected European transmission network that determines the investment decisions (in terms of the volume and the location of new generation and transmission network capacity) minimising the overall electricity system cost in Europe while satisfying security of supply requirements. WeSIM carries out an integrated optimisation of electricity system investment and operation and considers two different time horizons: (i) short-term operation with a typical resolution of one hour, which is coupled with (ii) long-term investment i.e. planning decisions with the time horizon of multiple years. All investment decisions and operation decisions are determined simultaneously in order to achieve an overall optimality of the solution. Figure 1 illustrates the structure of WeSIM.

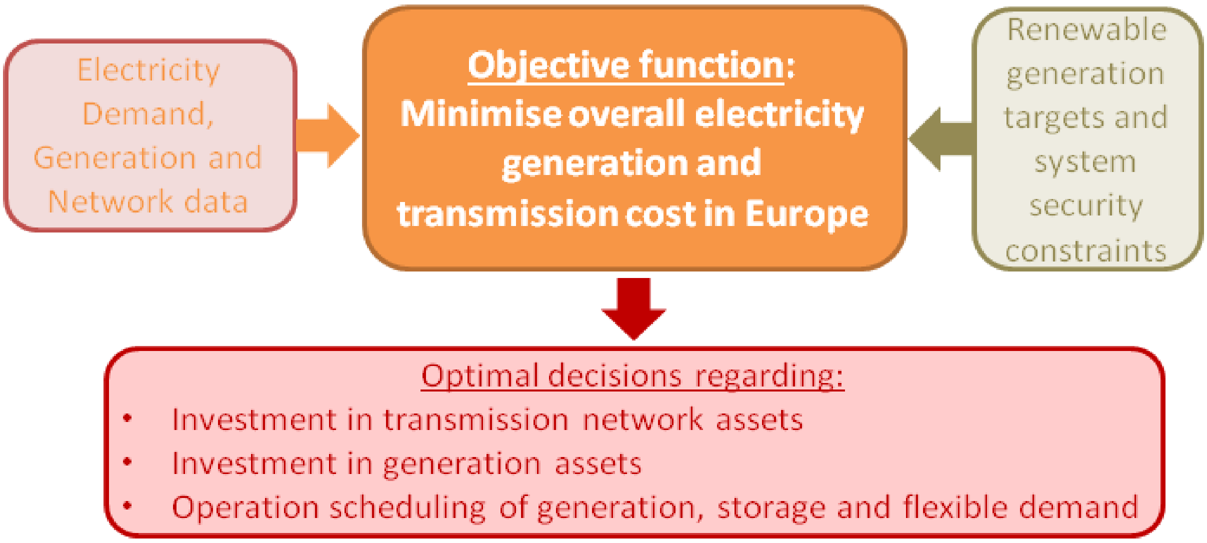

Figure 1: *Illustration of WeSIM model*

The objective function of *WeSIM* is to minimise the overall electricity system cost, which consists of investment and operating cost:

- The *investment cost* includes (annualised) capital cost of new generation and storage units, capital cost of new interconnection capacity, and the reinforcement cost of transmission networks. Various types of investment costs are annualised by using the appropriate Weighted-Average Cost of Capital (WACC) and the estimated economic life of the asset.
- The *operating cost* includes the annual generation operating cost and the cost of supply interruption driven by capacity inadequacies. The model captures part load efficiency losses and generation start up costs, while taking into account the dynamic characteristics of generating plants (minimum stable generation, minimum up and down times, ramp rates etc), which is a key to quantifying system integration cost of renewable generation and the role and value of FID.

There are a number of constraints that need to be respected by the model while minimising the overall cost. These include:

- *Power balance constraints*, which ensure that supply and demand at each node of the transmission network are balanced at all times.
- *Operating reserve constraints,* which ensure that sufficient capacity of fast frequency regulation and reserves are available for the secure operation of the electricity system on a second by second basis.
- *Adequacy constraints* ensure that there is sufficient generating capacity in the system to supply the demand with a given level of security.
- *Power flow constraints,* which limit the energy flowing through the lines between the different areas in the system, respecting the installed capacity of the network as an upper bound. The model can also invest in enhancing transmission and interconnection network capacity if this is cost efficient.
- *Renewable generation penetration constraints*, which ensure that a particular % ratio of electricity consumption is supplied by renewable generation sources.
- *Renewable generators (wind, solar etc) operating constraints*, which ensure that the maximum unit electricity production is limited by the availability of resource that is location specific. The model maximises the utilisation of these units since they are characterised by the lowest operating cost. In certain conditions when there is oversupply of electricity in the system or reserve/response requirements limit the amount of renewable generation that can be accommodated, it might become necessary to curtail their electricity output in order to balance the system and the model accounts for this.
- *Conventional generators (gas, coal, oil etc) operating constraints,* which include: (i) minimum stable generation and maximum output constraints; (ii) ramp-up and ramp-down constraints; (ii) minimum up and down time constraints; and (iv) available frequency response and reserve constraints.
- *Hydro generating units with reservoirs and pumped-storage units operating constraints*, which ensure that their electricity production is limited not only by their maximum power output but also by the energy available in the reservoir at a particular time (while optimising the operation of storage). The amount of energy in the reservoir at any given time is limited by the size of the reservoir. Minimum energy constraints and efficiency losses are taken into account.
- *FID operating constraints,* discussed in Section 3.1 and expressed by equations (1) and (2).

3.2.2 Stochastic Unit Commitment Model (SUCM)

As discussed before, the increased penetration of renewable generation in the European system is expected to significantly complicate system operation and enhance the volume of required ancillary services to balance demand and supply on a second by second basis i.e. reserve and frequency response services. In this context, the accurate representation of system operation requires advanced models capable of capturing the inherent system uncertainties through suitable stochastic techniques. For this purpose, Imperial College partners have developed the *Stochastic Unit Commitment Model* (SUCM) [9], which optimally schedules energy production and delivery of a number of balancing services in light of uncertainties associated with wind generation, demand and plant outages. Figure 2 illustrates the structure of the SUCM model.

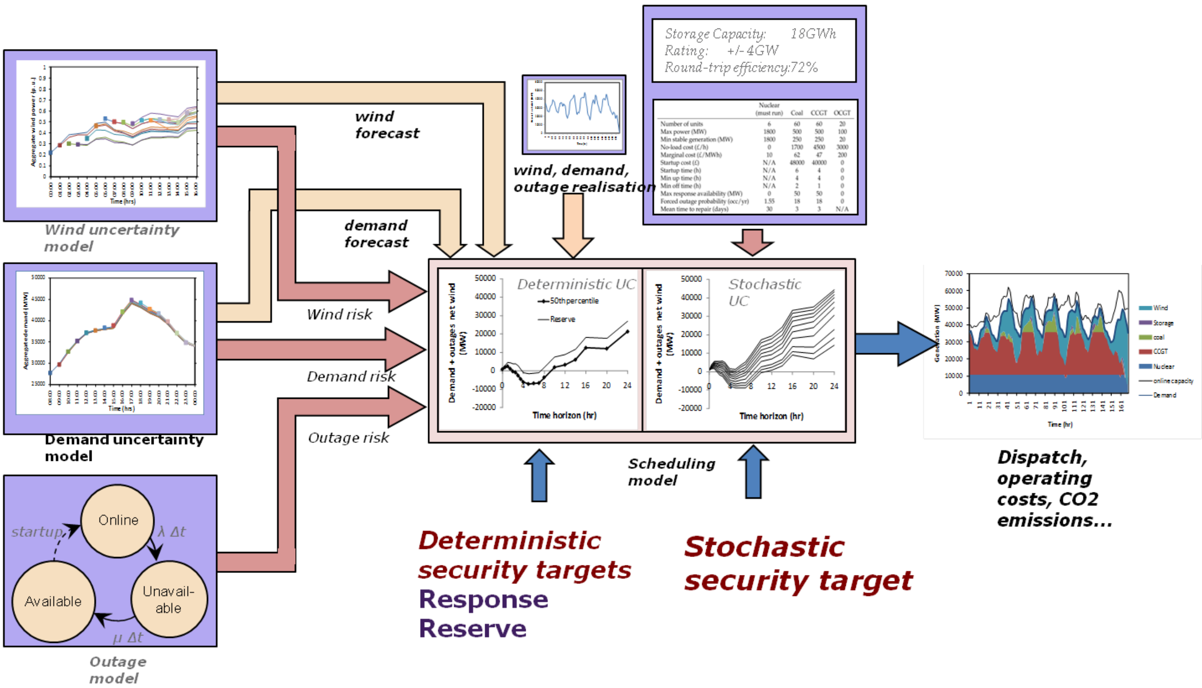

Figure 2: *Illustration of SUCM model*

This modelling framework includes two main parts: 1) statistical models to describe the system uncertainties; 2) system scheduling model to find the optimal commitment and dispatch decisions under deterministic or stochastic security rules.

Wind / solar generation and demand profiles as well as statistical information regarding forecasting errors and generation reliability are fed into the statistical models, which synthesise scenarios to build a scenario tree describing system uncertainties. The quintile-based scenario selection method is applied in this model by constructing and weighting scenario trees based on user-defined quantiles of the distribution of the net demand. Compared with commonly used Monte Carlo methods, this method captures critical information about the uncertainties by considering only a relatively small number of scenarios. The scenario generation process includes two steps: (a) creation of net demand distribution and (b) calculation of nodal value of net demand and associated probability.

The developed scenario tree is then fed into the scheduling model, which finds the optimal commitment and dispatch decisions under deterministic or stochastic security rules. The objective of stochastic scheduling is to minimize the expected operation costs (including generation costs and load shedding costs) over all possible scenarios. The optimization is subject to local load balance constraints, local or system primary/secondary frequency response constraints, transmission capacity limits as well as constraints for thermal units (such as minimum/maximum generation, commitment time, minimum up and down times, ramping rates, primary/secondary frequency response provision) and storage units (such as minimum/maximum power and energy limits, ramping rates, primary/secondary frequency response provision).

The simulations are carried out through a rolling planning approach, performing a complete calculation with a 24 hour horizon and an hourly time step, and discarding all decisions beyond the root node ones. In the next time step, realizations of some uncertain variables become available, which may be different from any existing scenario. An updated scenario tree covering a 24 hour time horizon is then built; operational decisions are adjusted and time coupling constraints are satisfied.

3.2.3 Distribution Network Planning Model (DistPlan)

As discussed before, the planning and operation of distribution networks are highly local tasks, as these networks are not interconnected and need to deal with local demand and generation conditions. For this reason, Imperial College partners have developed a *Distribution Network Planning Model* (DistPlan) [9] dealing exclusively with optimal distribution network planning decisions on an individual country basis. The aim of this model lies in determining the least-cost reinforcement decisions required for satisfying the future demand growth in each country.

The developed modelling approach includes three distribution network voltage levels, following the structure of distribution networks in Europe:

- *Low voltage (LV) networks*, which operate at around 0.4kV and are supplied from individual distribution substations.
- *Medium voltage (MV) networks,* which contain feeders with a voltage of approximately 6-20 kV, starting from HV/MV substations and finishing with distribution substations.
- *High voltage (HV) networks,* which contain assets from the Grid Supply Point, i.e. the connection to transmission (220-400 kV) or sub-transmission grids (72-132 kV) down to HV/MV substations.

Given that the size and diversity of distribution networks is very large and very limited data is publicly available regarding the actual topology and technical characteristics of real distribution networks, this model is based on analysing a limited number of statistically representative networks rather than actual networks. The use of statistically representative networks is motivated by the fact that the reinforcement cost in distribution networks tends to be driven by the network length, which can be expressed as a function of customer density. The consumer distribution pattern varies greatly from one area to another. An urban area has very different consumer distribution pattern than a rural area. Furthermore, the consumers are not normally distributed uniformly along the feeder. The conventional geometric model, which assumes equal spacing between the consumers, is not adequate to represent the consumer distribution realistically. In order to capture the consumer position and hence the network length more realistically, principles from the fractal theory are employed to generate statistically representative networks [10].

More specifically, fractal theory is used to create representative LV, MV and HV distribution networks that capture statistical properties of typical network topologies that range from high-load density city/town networks to low-density rural networks. In this procedure, the parameters of representative networks are calibrated against available high-level statistical information regarding the characteristics of actual distribution networks. Specifically, the representative networks are designed to represent the main features of real distribution networks of similar topologies, e.g. the number and type of consumers and load density, ratings of feeders and transformers used, associated network lengths and costs, etc. Examples of different distribution network topologies that are created by this modelling approach are shown in Figure 3 for urban, rural and mixed areas, characterised by different consumer densities.

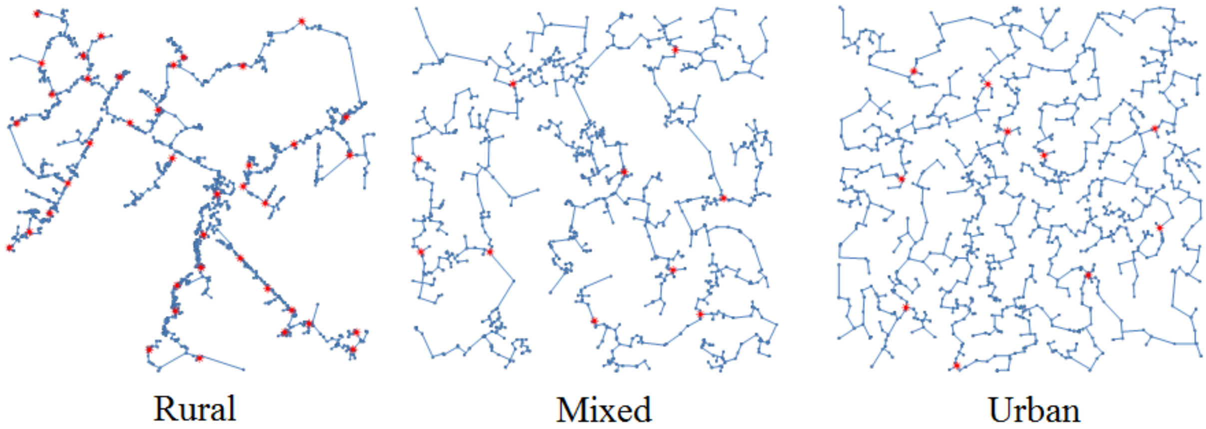

Figure 3: *Illustration of different distribution network topologies*

This method allows formulation of computationally feasible analytical models with only a minor sacrifice in terms of the accuracy of estimating reinforcement costs. Using a limited number of these statistically representative network types, although not representing any particular physical networks, results in computationally efficient, yet very accurate estimates of reinforcement costs in larger areas.

3.3 Bottom-up quantification of FID benefits

The modelling approaches presented in Section 3.2 are used in the IndustRE project for the top-down quantification of FID benefits i.e. for the quantification of the electricity system cost savings brought by FID. Under a suitable market and regulatory framework, part of the system cost savings should be transferred to the flexible industrial consumers in order to remunerate them for the flexibility they provide to the system and encourage further flexibility provisions.

In order to quantify these cost savings of flexible industrial consumers, the Imperial College partners have developed a new model, referred to as *Bottom-Up Quantification Model* (BUQM) in the remainder of this report and founded on the principles presented in publications [11]-[13]. This model represents the perspective of a single industrial consumer, which aims at minimizing its total electricity cost by making optimal use of its flexibility.

As discussed in Chapters 2 and 3, the system cost savings brought by FID span across multiple time horizons (long-term planning, short term scheduling, and real-time balancing) and multiple sectors (generation, transmission, and distribution) of the power system. This means that under a suitably designed market and regulatory framework, flexible industrial consumers should be able to simultaneously provide multiple different services and thus access multiple value streams. Based on the discussion in Chapters 2 and 3 as well as the analysis presented in the previous IndustRE deliverable D2.1 [14], these value streams include:

- *Energy cost savings*: This value stream corresponds to the reduction of the flexible industrial consumer's energy bill and is associated with its ability to adjust its electricity consumption pattern according to the temporal variation of energy prices. This temporal variation of energy prices is driven by the variation of the total demand and renewable generation levels in the system. Therefore, this value stream is implicitly associated with the ability of FID to enable higher energy production by renewable and low-cost generation sources.
- *Revenues from provision of balancing services*: This value stream is associated with the ability of FID to provide reserve and frequency response services to the system, reducing the efficiency losses of conventional generators and the curtailment of renewable generation. More specifically, a flexible industrial consumer can offer the capability to either increase or decrease its demand with respect to the amount they have procured in the energy market, in case an imbalance occurs between the total generation and total demand in the system. Under a suitable market framework industrial consumers should be remunerated for the provision of such balancing services on a level playing field with generators, based on cost-reflective balancing prices.

- *Revenues from provision of generation / transmission / distribution capacity services*: This value stream is associated with the ability of flexible industrial demand to avoid / defer investments in generation and transmission / distribution networks assets. Under a suitable market framework industrial consumers should be remunerated for the avoidance / deferral of such capital-intensive investments, based on cost-reflective capacity prices.

The BUQM considers all these value streams and its objective function is to minimise the total electricity cost of a flexible industrial consumer, as expressed by equation (3):

$$Min\left\{\sum_t\left[d_t^{flex}\cdot\pi_t^E-(BS_t^{IN}+BS_t^{DE})\cdot\pi_t^{BS}\right]-\left(\overline{d_t^{base}}-\overline{d_t^{flex}}\right)\cdot(\pi^{GC}+\pi^{TC}+\pi^{DC})\right\} \quad (3)$$

This objective function includes:

- *Energy cost*: this is defined for each hour t as the product of the final power demand d_t^{flex} of the industrial consumer multiplied by the energy price π_t^E.
- *Revenue from provision of balancing services*: this is defined for each hour t as the offered volume of balancing services (capability to either increase demand by BS_t^{IN} or decrease demand by BS_t^{DE} with respect to the amount d_t^{flex} procured in the energy market) multiplied by the balancing services price π_t^{BS}.
- *Revenue from provision of generation / transmission / distribution capacity services*: given that investments in generation and network capacity are fundamentally driven by peak demand levels, this revenue is defined for the whole horizon of the analysis (one year) as the reduction of the industrial consumer's peak demand brought by the deployment of flexibility $(\overline{d_t^{base}}-\overline{d_t^{flex}})$ multiplied by the generation / transmission / distribution capacity price respectively.

Certain constraints need to be respected by the model while minimising the overall cost. These include:

- *Operating constraints of the flexible industrial consumer*: these are discussed in Section 3.1 and are expressed by equations (1) and (2).
- *Balancing services provision limits*: the maximum amount of the demand increase capability BS_t^{IN} offered by the industrial consumer is given by the difference between its maximum demand i.e. $(1+a)*d_t^{base}$ according to equation (1), minus its demand in the energy market d_t^{flex}; on the other hand, the maximum amount of the demand decrease capability BS_t^{DE} offered by the industrial consumer is given by the difference between its demand in the energy market d_t^{flex} minus its minimum demand i.e. $(1-a)*d_t^{base}$ according to equation (1).

Figure 4 illustrates the structure of BUQM. By simultaneously considering the above energy, balancing and capacity value streams, the BUQM model inherently accounts for interdependencies and conflicts between the provisions of different services by the flexible industrial consumer. For example, the consumer can exploit periods with low energy prices by increasing its demand during these periods in order to reduce its energy costs; however, this action can potentially increase its peak demand, leading to lower revenues from the capacity markets. The model optimizes the allocation of the consumer's flexibility among conflicting services, given the market prices associated with these services.

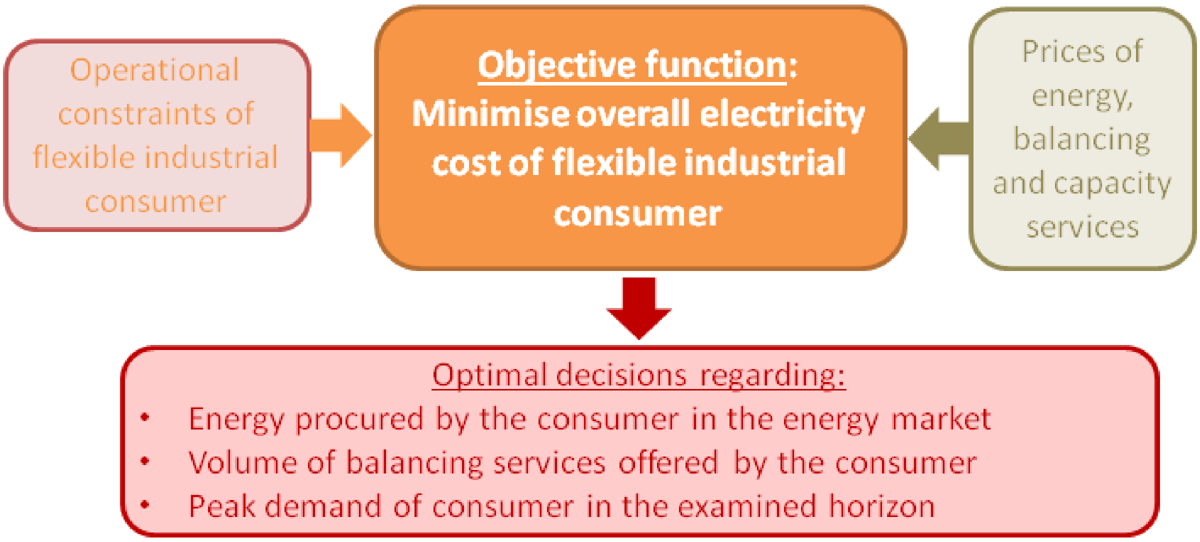

Figure 4: *Illustration of BUQM model*

It is evident that the outcomes of this bottom-up quantification of FID benefits depends to a great extent on the electricity market framework, involving a) the market rules associated with the participation of different entities in energy, balancing and capacity markets and b) the pricing mechanisms associated with energy, balancing and capacity products. Changes in the market regulation and the pricing mechanisms obviously have a major impact on the cost savings that deployment of flexibility can bring to an industrial consumer. As discussed in detail in the previous IndustRE deliverable D2.2 [15], the different aspects of the electricity market framework vary significantly among the 6 target countries of the project. Furthermore, as discussed in detail in the previous deliverables D2.3 [16] and D2.4 [17], the existing electricity market frameworks of most European countries still exhibit significant inefficiencies which do not allow the full realization of the potential of FID and demand flexibility in general.

The objective of this task of the IndustRE project (Task 5.2) is the quantification of the cost savings of a flexible industrial consumer under an "ideal" electricity market framework, which involves cost-reflective pricing mechanisms, does not impose excessive constraints on the potential market participants and is uniform across the different European countries. It is obvious that the development of an "ideal" market framework is an extremely difficult and complicated task, in both theoretical and practical terms. A large number of relevant market design activities are currently led by the European Commission, governments, industry and academia, and although a general consensus has been reached regarding some of the aspects of such an “ideal” market framework (e.g. the economic advantages of time- and location-dependent energy prices), intense ongoing debates and conflicting views have been witnessed around other aspects (e.g. the design of capacity markets for which limited practical experience exists in Europe).

In this context, the IndustRE partners contributing to this deliverable report do not claim that the market framework simulated in this bottom-up quantification of benefits is an “ideal” one. Furthermore, it should be noted that more detailed recommendations by the IndustRE consortium regarding a suitable market design will be provided by the deliverable 5.3, which will also account for practical insights from the project’s case studies and is currently under preparation. However, the authors of this deliverable report have made a number of assumptions regarding certain aspects of such an “ideal” market framework, which they believe are in line with the main conclusions of relevant research, industrial and policy activities in Europe:

- *Energy pricing mechanism:* The energy market prices are determined based on locational marginal pricing principles, accounting for both the temporal and locational dependency of energy production costs. In order to ensure that these prices are cost-reflective, the authors have derived them from the outcomes of European power system optimization performed by Task 5.1 and discussed in Section 3.2 and Chapter 4. More specifically, the energy price at each time period and each node of the European transmission network corresponds to the Lagrangian multiplier associated with the power balance constraint of the SUCM model at the same time period and network node. In other words, the employed energy prices reflect the temporal and locational conditions in an optimally (i.e. least-cost) designed and operated European power system.
- *Balancing services pricing mechanism:* As discussed in Section 3.2, real-time system balancing is an extremely challenging task and advanced stochastic modelling and optimization tools are required in order to perform it in a cost-efficient manner. In this complex setting, locational marginal pricing principles cannot be easily applied in balancing markets for both theoretical and practical reasons. Therefore, in order to derive cost-reflective prices for Task 5.2, an “opportunity cost” pricing approach based on the outcomes of the European power system optimization is employed. More specifically, the balancing-related European operating cost savings brought by FID at each time period (as quantified by the SUCM model, see Sections 3.2.2 and 4.1) are divided by the total amount of balancing power provided by FID at the same time period (as also determined by the SUCM model); this division provides the price for the provision of balancing services at each time period of the examined horizon.
- *Capacity services pricing mechanism*: Investments in generation, transmission and distribution capacity are characterized by economies of scale, meaning that they

involve significant fixed capital costs which do not depend on the amount of generation / network capacity procured (e.g. costs of land, labour etc). According to the economic theory, marginal prices cannot capture these fixed cost components. Therefore, in a similar fashion with the balancing pricing mechanism discussed above, an "opportunity cost" pricing approach based on the outcomes of the European power system optimization is employed. Given that investments in generation and network capacity are fundamentally driven by peak demand levels, the generation, transmission and distribution capital cost savings brought by FID are divided by the peak demand reduction driven by the FID; this division provides the price for the provision of generation / transmission / distribution capacity services. The peak demand reduction and the capital cost savings at the interconnected generation and transmission European system are quantified by the WeSIM model (see Sections 3.2.1 and 4.1) while the peak demand reduction and the capital cost savings at the distribution system of each of the 6 target countries of IndustRE are quantified by the DistPlan model (see Sections 3.2.3 and 4.2).

- *Market coupling at the generation and transmission level*: As discussed in Section 3.2, European countries are already interconnected through high-voltage interconnection links and interconnection projects are expected to increase due to the benefits of exploiting the natural diversity of different renewable generation technologies in different countries and enhancing the cost-efficiency of the European electricity system. This is the reason why the FID economic benefits at the generation and transmission level are quantified in this report for the interconnected European power system as a whole (see Section 3.2 and 4.1). In this context, Task 5.2 assumes the unification (or coupling) of the different countries' markets for energy, balancing services, generation capacity and transmission capacity services; in other words, a single European-wide market is assumed for each of the above products, in which generators and consumers from the whole Europe participate. Concerning balancing and capacity markets, given that an "opportunity cost" pricing approach is employed, this unification means that the same balancing and capacity prices apply to all industrial consumers in Europe irrespectively of their location. Concerning the energy market however, given that locational marginal pricing is employed, this unification does not necessarily mean that the same energy prices apply to all industrial consumers; in cases of network congestion, different energy prices generally apply to consumers in different nodes of the European network.
- *Country-specific markets at the distribution level*: On the other hand, distribution networks of different countries are not interconnected and need to deal with local demand and generation conditions. This is the reason why the FID economic benefits at the distribution level are quantified in this report for each of the 6 target countries of IndustRE separately (see Section 3.2 and 4.2). In this context, Task 5.2 assumes

that a separate market for distribution capacity services operates in each of these 6 countries and therefore a different distribution capacity price applies to industrial consumers in different countries.

- *Neglecting limitations and practical constraints imposed by current market regulation*: As discussed in detail in the previous IndustRE deliverable D2.4 [17], the existing electricity market frameworks of most European countries exhibit significant limitations and practical constraints regarding the participation of consumers in the electricity market which do not allow the full realization of the potential of FID and demand flexibility in general. A few examples include: a) capacity markets are completely absent from most European countries meaning that the value of FID in avoiding / deferring investment in generation / network capacity is not remunerated, b) most of the existing balancing markets in European countries impose a high minimum size limit and / or a high minimum availability limit to demand participants. The IndustRE partners contributing to this deliverable report do not underestimate the significant practical challenges driving these barriers; on the contrary, these barriers have been thoroughly examined in the previous deliverables D2.3 [16] and D2.4 [17], and detailed recommendations for addressing them will be provided by the deliverable 5.3 which is currently under preparation. However, the IndustRE partners believe that an “ideal” electricity market framework should remove these barriers. For this reason, limitations and practical constraints imposed by current market regulation are neglected in Task 5.2.

4. Studies and findings on top-down quantification of FID benefits

This chapter presents the examined studies, the data sources used and the obtained results regarding the top-down quantification of FID economic benefits. For the reasons discussed in Section 3.2, the benefits for the European generation / transmission system and the benefits for the 6 target countries’ local distribution systems are separately assessed, and the details of these assessments are presented in Section 4.1 and 4.2 respectively.

The modelling horizon for both assessments is 2030. In other words, the deployed models use projections of demand and renewable generation levels on 2030 and optimize investment and operation decisions to minimize the system costs required to satisfy these projections.

4.1 Assessment of FID benefits for the European generation / transmission system

In order to assess the economic benefits of FID at the European electricity system level, a simplified yet representative model of the European interconnected transmission network has been employed in IndustRE, developed as part of the report [18] and illustrated in Figure 5. This model does not only cover the 6 target countries of the project (Belgium, France, Germany, Italy, Spain and UK) but also all member states that are physically part of the interconnected electricity market within the EU, and provides a comprehensive representation of the continental European grid. The total number of network zones (or nodes) in this model is 74, spreading over 31 European countries. These nodes are linked through 166 interconnectors, representing either existing or potential interconnection links. The networks of larger countries (e.g. France, Germany, Spain) are represented by multiple network zones, in order to reflect internal network congestion effects and the need for transmission network reinforcements. On the other hand, smaller countries (e.g. Belgium, Netherlands, Portugal) are represented by a single network zone, due to the small size of their power systems. The capacity of each existing interconnector is determined by the Grid Transfer Capability (GTC) which specifies the ability of the European grid to transport electricity across a given boundary. The values of the GTC as well as data used for the costs of transmission expansions / reinforcements are detailed in [18, Section 2.2].

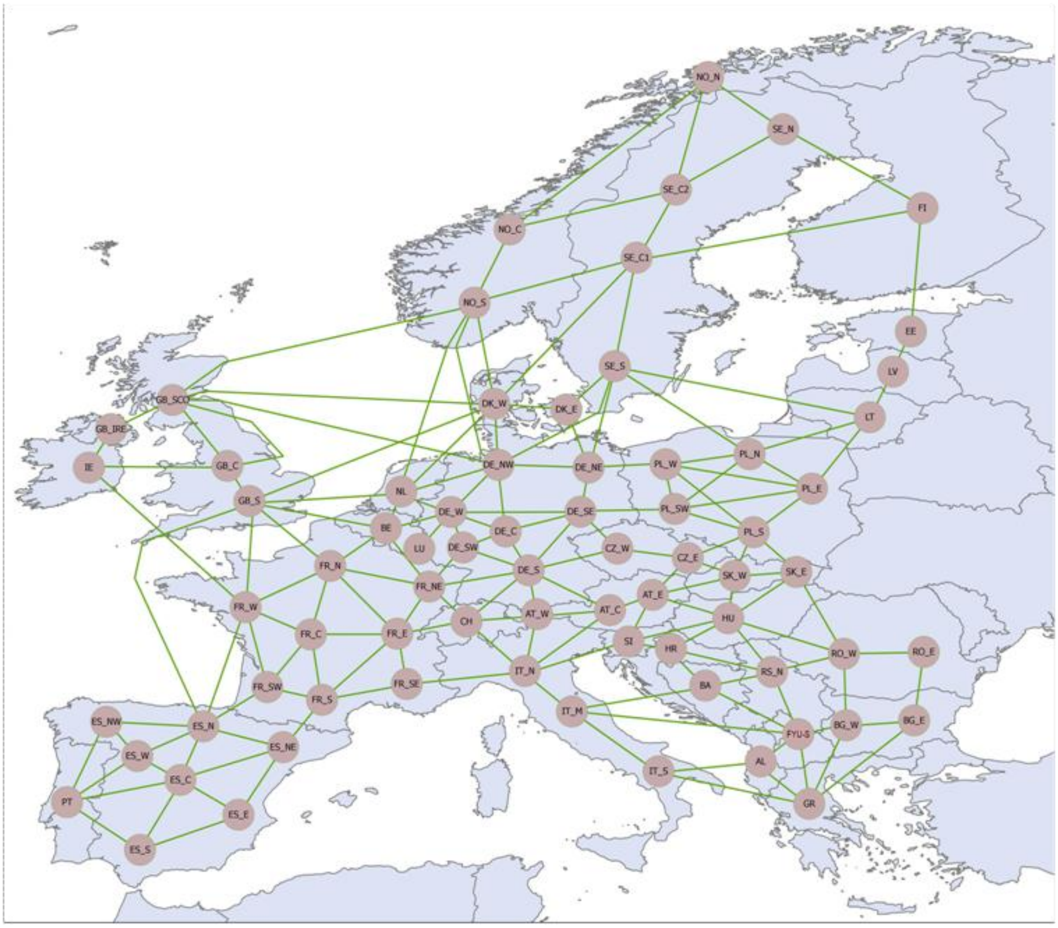

Figure 5: *Model of European interconnected transmission network*

Regarding the generation system, the various conventional and renewable generators in Europe have been grouped into basic generation technologies, the detailed technical and cost characteristics of which are detailed in [18, Section 2.1.2]. According to [19, page 6], renewable generation is expected to cover around 45% of the overall electricity consumption in Europe in 2030. In this context, two alternative scenarios regarding the level of renewable generation penetration in the European system in 2030 are considered. Specifically, these scenarios involve 30% and 60% of the overall electricity consumption in Europe to be supplied by renewable generation sources (denoted in the remainder of this report as *30% RES* and *60% RES* scenarios respectively) and express a pessimistic and optimistic pathway for the integration of renewable generation in Europe respectively.

Regarding the demand side, the total electricity consumption and the industrial electricity consumption per European country in 2030 follow the Eurostat projections [20]. Figure 6 presents the share of industrial over the total electricity consumption for different European countries, where the 6 target countries of IndustRE are denoted in red colour.

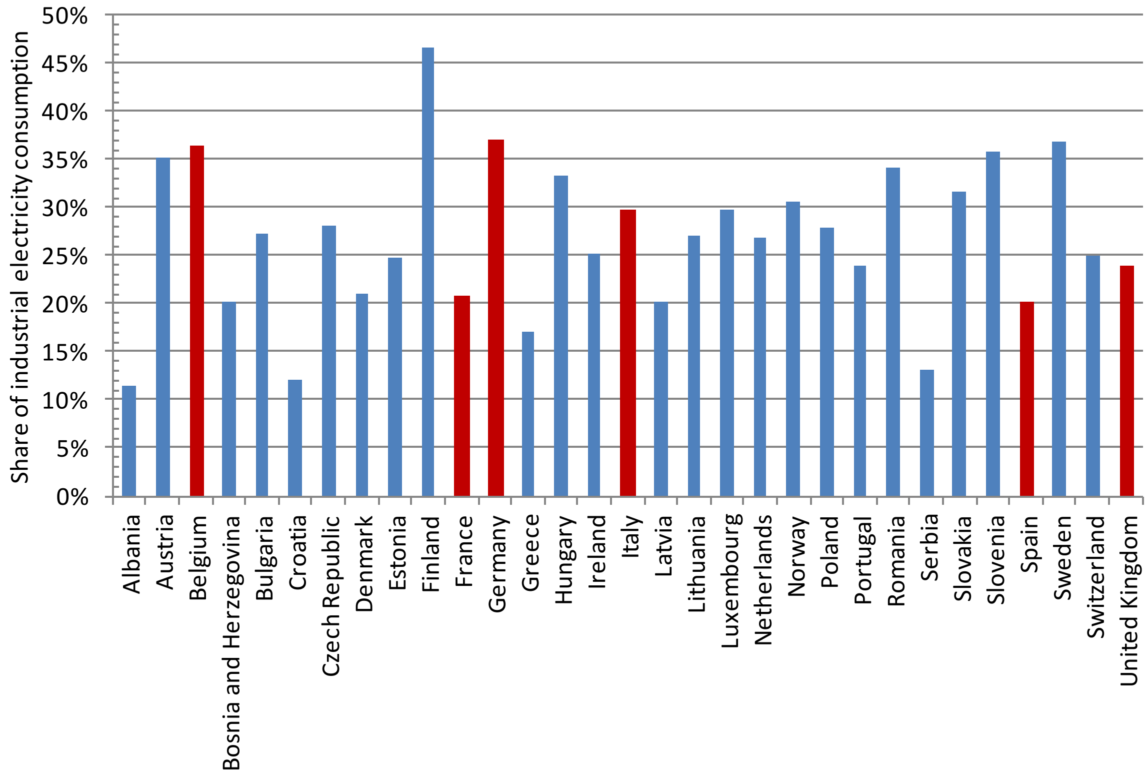

Figure 6: *Share of industrial over total electricity consumption for different European countries. The target countries of IndustRE are demoted in red colour.*

As discussed in Section 3.1, alternative scenarios are examined regarding the extent of industrial demand flexibility, expressed by the ratio a in equation (1). Specifically, the examined scenarios include the values $a = 1\%$, $a = 5\%$, $a = 10\%$, $a = 20\%$, and $a = 50\%$, along with the benchmark scenario $a = 0\%$ which corresponds to a case without any industrial demand flexibility.

The above generation, demand and interconnected transmission network data are used by the WeSIM (Section 3.2.1) and SUCM (3.2.2) models to determine the European generation and transmission investment and operation decisions minimizing the overall system costs.

As discussed in Section 3.2, a two-stage approach is employed to achieve this. The WeSIM model determines optimal generation and transmission investment and operation decisions at the whole European level, by employing however a simplified deterministic representation of system operation not capturing uncertainty factors. The investment decisions of the WeSIM model are then inputted to the SUCM model which refines operation decisions by capturing uncertainty factors through advanced stochastic modelling and optimization techniques.

This process is carried out for all the combinations of each of the examined renewable generation and industrial demand flexibility scenarios (2 renewable generation scenarios * 6 industrial demand flexibility scenarios = 12 scenarios overall). The differences in the obtained results between the benchmark scenario $a = 0\%$ (which corresponds to a case without any industrial demand flexibility) and each of the scenarios with some positive industrial demand flexibility ($a = 1\%$, $a = 5\%$, $a = 10\%$, $a = 20\%$, and $a = 50\%$) express the impacts of FID on the development and operation of the European generation and transmission system. The most significant impact that this report aims to quantify is the difference in the overall generation and transmission costs, which express the cost savings brought by FID.

Figure 7 presents the generation and transmission cost savings (in billion Euros per year) brought by different levels of industrial demand flexibility (with respect to the benchmark scenario $a = 0\%$) and the two examined scenarios regarding the level of renewable generation.

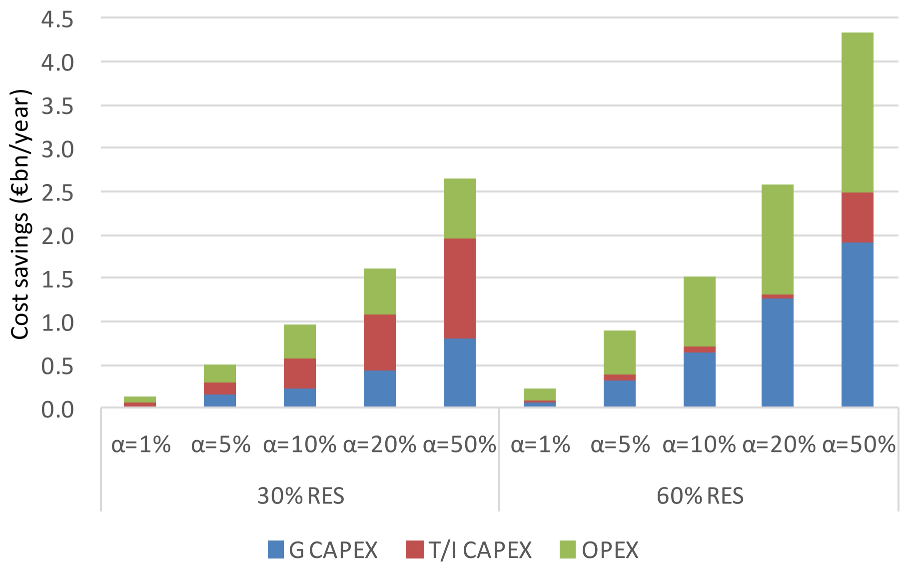

Figure 7: *European electricity generation and transmission cost savings (in €bn/year) brought by FID for different scenarios of industrial demand flexibility and renewable generation.*

The three different colours on each column represent different streams of cost savings brought by FID:

- ***G CAPEX*** (denoted in blue colour): savings in capital costs brought by avoiding investments in additional generation capacity.
- ***T/I CAPEX*** (denoted in red colour): savings in capital costs brought by avoiding investments in additional transmission and interconnection capacity.
- ***OPEX*** (denoted in green colour): savings in operational costs brought by enabling higher energy production by renewable and low-cost generation sources and providing balancing services (thus reducing the efficiency losses of conventional generators).

As expected, higher levels of industrial demand flexibility (higher values of a) enhance the different streams of cost savings and increase the total cost savings, for both renewable generation scenarios. Under a 30% RES scenario, the total cost savings vary between 136 million Euros per year (for $a = 1\%$) to 2.65 billion Euros per year (for $a = 50\%$). Under a 60% RES scenario, the total cost savings vary between 232 million Euros per year (for $a = 1\%$) to 4.34 billion Euros per year (for $a = 50\%$).

Furthermore, it is observed that the generation capital (G CAPEX) and operational (OPEX) cost savings for each of the industrial demand flexibility scenarios (for each value of a) are significantly higher under the 60% RES scenario compared to the 30% RES scenario. This is because higher renewable generation levels make system balancing more challenging and increase the requirements of flexibility in the European system. On the other hand, it is observed that the capital cost savings in transmission and interconnection (T/I CAPEX) capacity are higher under the 30% RES scenario. This trend is justified by the fact that network investments are generally cheaper than generation investments and they are mainly driven by the peak demand levels. As a result, under a higher penetration of renewable generation (60% RES), industrial demand flexibility is primarily used to support cost-efficient system balancing and avoid expensive investments in flexible conventional generation units (such as OCGT and oil generators), and to a less extent for the reduction of peak demand levels and the avoidance of cheaper network investments. Under a lower penetration of renewable generation (30% RES), the system balancing burden is lower, and therefore industrial demand flexibility can support further the reduction of peak demand levels and the avoidance of network investments.

All in all, the total cost savings are significantly higher under the 60% RES scenario compared to the 30% RES scenario, since the additional G CAPEX and OPEX savings under the 60% RES scenario dominate the additional T/I CAPEX savings under the 30% RES scenario. This trend demonstrates the synergy between increased penetration of renewable generation and industrial demand flexibility, which constitutes a fundamental result of the IndustRE project.

An alternative way to quantify the generation and transmission cost savings of FID lies in expressing the absolute savings of Figure 7 as a percentage of the overall generation and transmission costs in the benchmark scenario without industrial demand flexibility. The resulting % savings are presented in Figure 8. It can be observed that the total cost savings vary between 0.1% (for $a = 1\%$ under 30% RES) to 6.3% (for $a = 50\%$ under 60% RES).

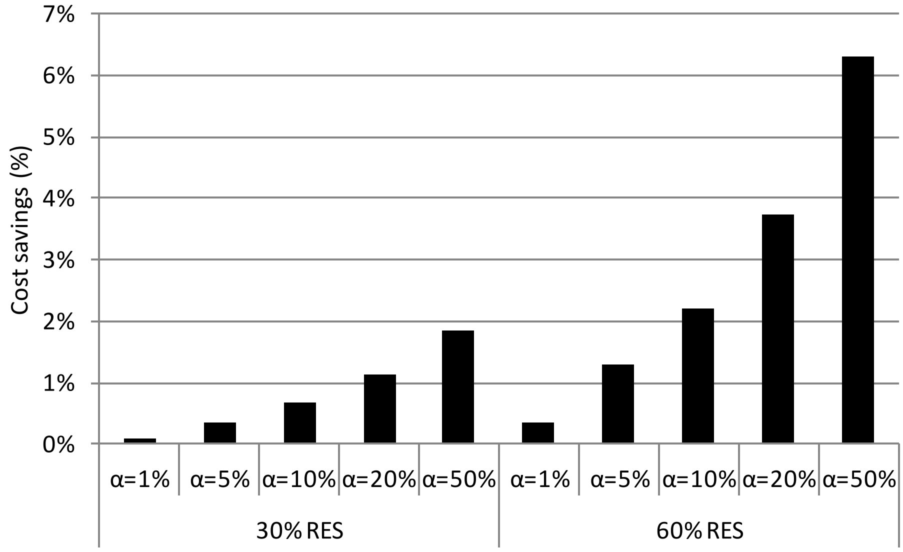

Figure 8: *European electricity generation and transmission cost savings (in %) brought by FID for different scenarios of industrial demand flexibility and renewable generation.*

The operational cost savings brought by FID (green part in Figure 7) can be further divided to different value streams, as demonstrated in Figure 9.

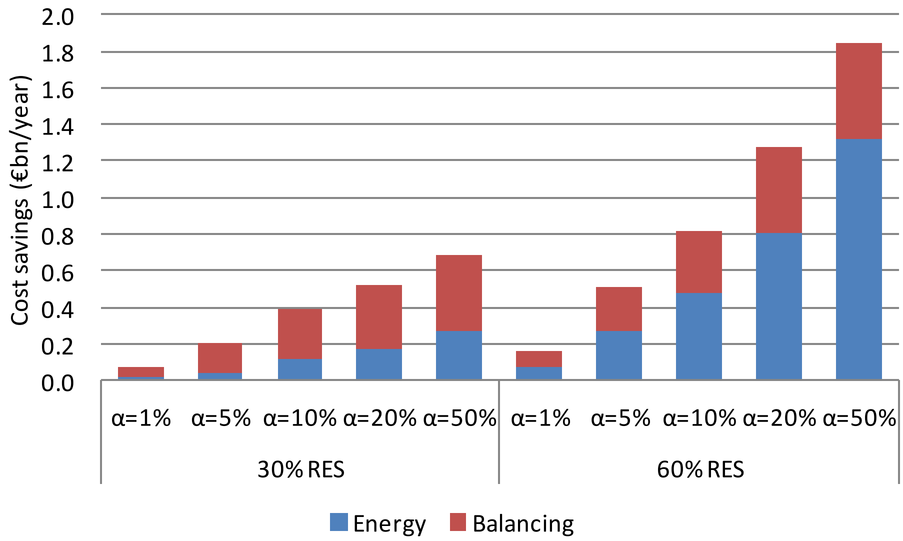

Figure 9: *European electricity operational cost savings (in €bn/year) brought by FID for different scenarios of industrial demand flexibility and renewable generation.*

The two different colours on each column represent:

- ***Energy*** (denoted in blue colour): savings in operational costs incurred for producing the energy consumed by the European consumers, brought by enabling higher energy production by renewable and low-cost generation sources.
- ***Balancing*** (denoted in red colour): savings in operational costs incurred for providing the required balancing services (reserves and frequency response), making sure that supply and demand are always balanced despite uncertainties in renewable generation production and generation / transmission assets' failures.

As expected, higher levels of industrial demand flexibility (higher values of a) enhance each of the two streams of operational cost savings and increase the total cost savings, for both renewable generation scenarios. Furthermore, as discussed before, these operational cost savings are significantly higher under the 60% RES scenario compared to the 30% RES scenario, since higher renewable generation levels make system balancing more challenging and increase the requirements of flexibility in the European system.

Beyond the cost savings demonstrated above, FID has also significant impacts on the way different generation sources are utilised. Figure 10 presents the changes in the annual energy output of different generation technologies in Europe (denoted in different colours) as a result of the deployment of different levels of industrial demand flexibility (with respect to the benchmark scenario $a = 0\%$), under the 60% RES scenario. Positive / negative values imply that the respective generation technologies produce more / less energy with the deployment of FID.

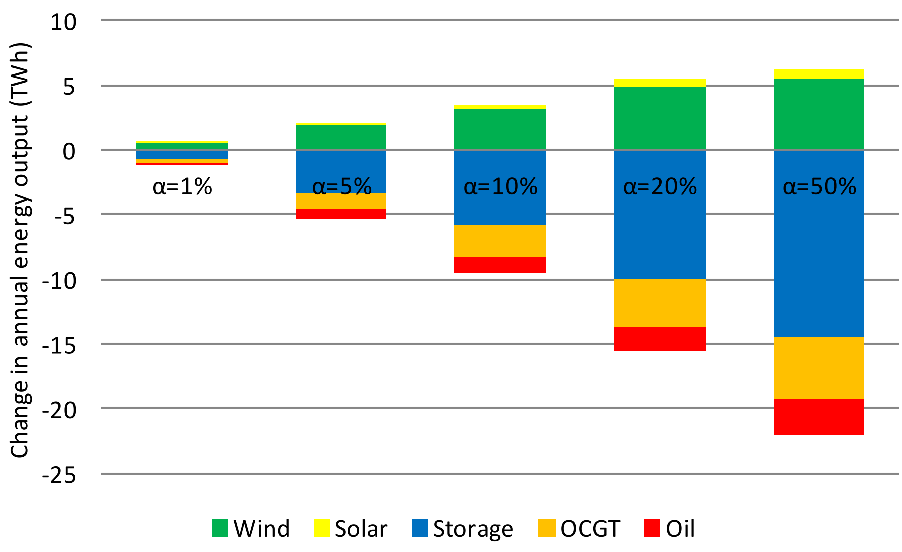

Figure 10: *Impact of different industrial demand flexibility levels on the annual energy output of different generation technologies.*

It can be observed that as the industrial demand flexibility level increases, peaking generation units (OCGT and oil generators) and storage units are used less, since FID limits peak demand levels and replaces these units in the provision of system balancing services.

This trend demonstrates the competition between demand flexibility, peaking generation and storage in the future European system setting. On the other hand, it is observed that as the industrial demand flexibility level increases, the utilisation of available renewable generation (mainly wind and solar) increases -or equivalently the curtailment of available renewable generation reduces- since FID can shift energy consumption to periods with increased renewable energy output and provide system balancing and frequency response services. This trend again demonstrates the synergy between increased penetration of renewable generation and industrial demand flexibility.

Interesting results are also observed around the way the available industrial demand flexibility is utilised. In this context, we define and quantify the utilisation of FID as the % ratio between the industrial energy consumption that is actually shifted across time under the optimal investment and operation decisions determined by the WeSIM and SUCM models over the maximum industrial energy consumption that can be shifted in time. This parameter expresses the extent to which the available flexibility of industrial consumers is actually utilised to support the cost-efficient planning and operation of the European system.

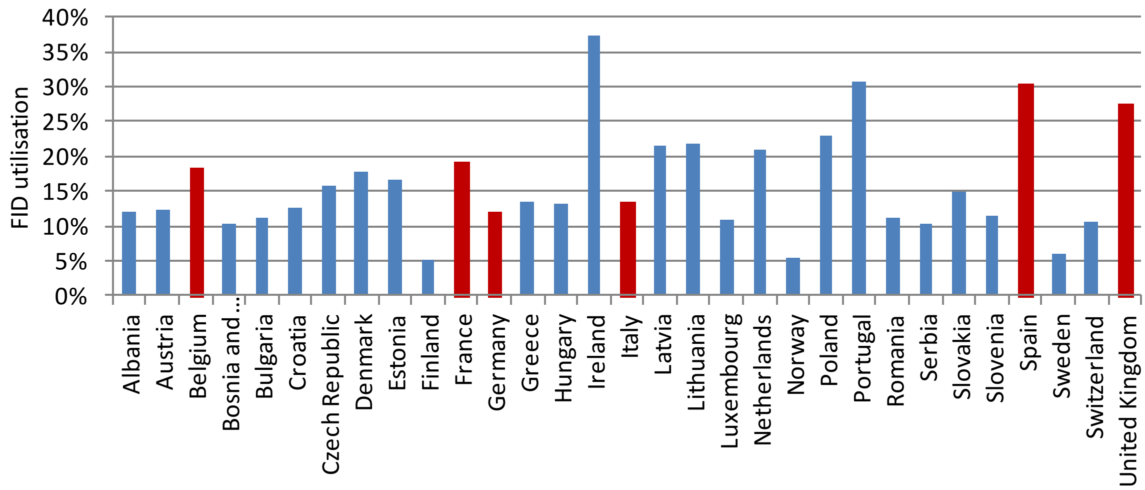

Figure 11: *Utilisation of industrial demand flexibility for different European countries. The target countries of IndustRE are denoted in red colour.*

Figure 11 presents the utilisation of FID at each country of the examined European network, for a scenario with $a = 20\%$ and 60% RES. It is observed that the utilisation of FID varies greatly across different countries. Relatively "isolated" countries (i.e. countries with limited interconnections with other countries), such as Ireland, Portugal, Spain and the United Kingdom, are characterized by higher utilisation of FID, given that their system balancing is more challenging and requires higher levels of flexibility. On the other hand, countries with significant interconnections with other countries and high levels of flexible generation (e.g. hydro), such as Finland, Norway and Sweden, are characterised by lower utilisation of FID, given that interconnections and flexible generation limit the value of additional flexibility. This trend demonstrates the competition between demand flexibility, generation flexibility and interconnections in the future European system setting.

Figure 12 breaks down the utilisation of FID at each country of the network into the utilisation at each season of a year, for a scenario with $a = 20\%$ and 60% RES. It is observed that FID is utilised significantly more during winter and significantly less during summer. This trend is associated with the fact that winter exhibits the highest peak demand levels and the highest output of wind generation, increasing the flexibility requirements.

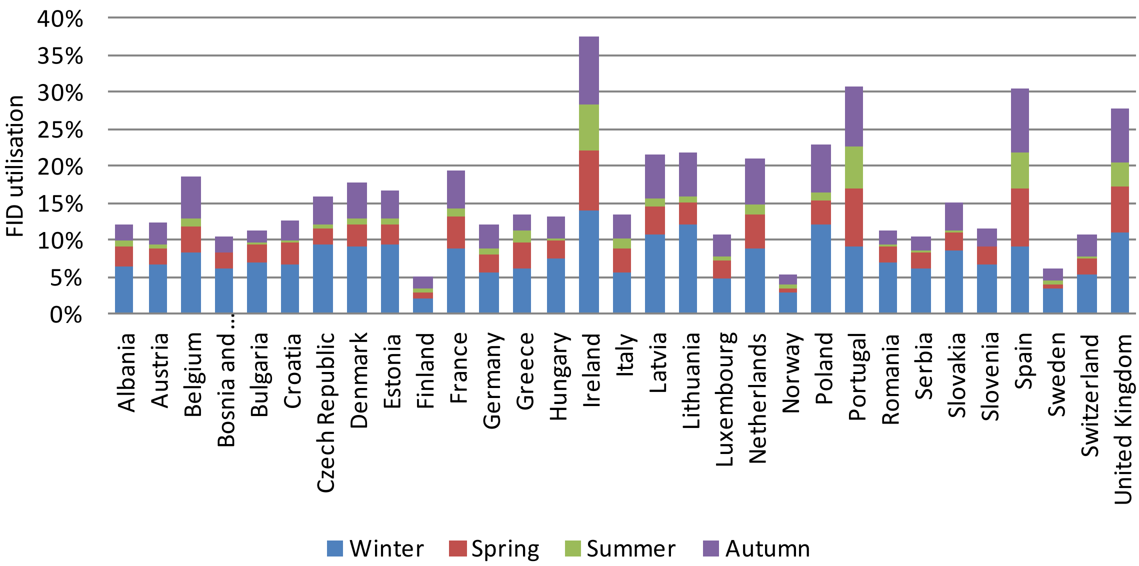

Figure 12: *Utilisation of industrial demand flexibility for different European countries and different seasons of the year.*

4.2 Assessment of FID benefits for the distribution networks of the 6 target countries

As discussed in Section 3.2.3, in order to assess the economic benefits of FID for the distribution system of each target country, a number of statistically representative networks are analysed, given that the size and diversity of distribution networks is very large and very limited data is publicly available regarding the actual topology and technical characteristics of real distribution networks. In order to generate these representative networks, statistical information regarding the population density, typical network design policies and standards in the 6 target countries of the project has been employed, as detailed in [18, Section 2.3.2]. Furthermore, the data used for the costs of different distribution assets' reinforcements are detailed in [18, Section 2.3.3].

As in the analysis of the benefits for the European generation / transmission system (Section 4.1), the total electricity consumption and the industrial electricity consumption for each of the 6 target countries in 2030 follow the Eurostat projections [20]. Based on data sources included in [18], it has been assumed that 60% of the overall industrial demand in each country is connected to the distribution network and specifically the HV level of the network. The rest of the industrial demand is assumed connected directly to the transmission network of the country and therefore its flexibility does not affect the reinforcement decisions in the distribution network.

As in Section 4.1, alternative scenarios are examined regarding the extent of industrial demand flexibility, expressed by the ratio a in equation (1). Specifically, the examined scenarios include the values $a = 1\%$, $a = 5\%$, $a = 10\%$, $a = 20\%$, and $a = 50\%$, along with the benchmark scenario $a = 0\%$ which corresponds to a case without any industrial demand flexibility. In contrast to Section 4.1, alternative scenarios regarding the level of renewable generation in the European system are not examined, since it is assumed that the vast majority of renewable generation is connected to the transmission network of the different countries and therefore does not have a major impact in the context of this study.

The generated representative networks along with the above cost and demand data are used by the DistPlan model (Section 3.2.3) to determine the least-cost distribution reinforcement decisions for each country while satisfying the 2030 demand levels. This process is carried out for each of the 6 industrial demand flexibility scenarios. The differences in the obtained results between the benchmark scenario $a = 0\%$ (which corresponds to a case without any industrial demand flexibility) and each of the scenarios with some positive industrial demand flexibility ($a = 1\%$, $a = 5\%$, $a = 10\%$, $a = 20\%$, and $a = 50\%$) express the impacts of FID on the development and operation of the distribution systems of the 6 target countries of the project.

Figure 13 presents the capital cost savings in distribution network reinforcements (in million Euros per year) brought by different levels of industrial demand flexibility (with respect to the benchmark scenario $a = 0\%$). Figure 14 presents the same cost savings as a percentage of the overall distribution network costs in the benchmark scenario $a = 0\%$. These savings are driven by the beneficiary impact of industrial demand flexibility in reducing peak demand levels. As expected, higher levels of industrial demand flexibility (higher values of a) increase these cost savings.

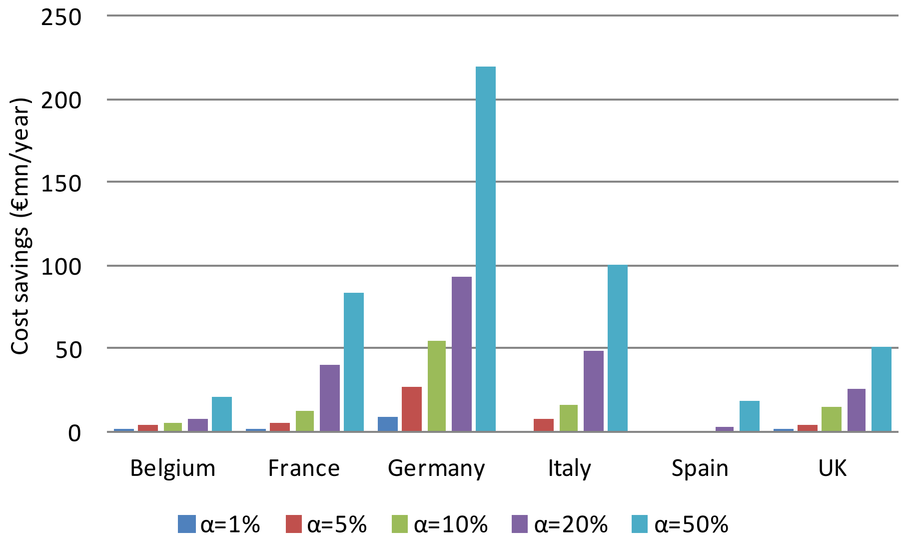

Figure 13: *Electricity distribution cost savings (in €mn/year) brought by FID in the 6 target countries of IndustRE for different scenarios of industrial demand flexibility.*

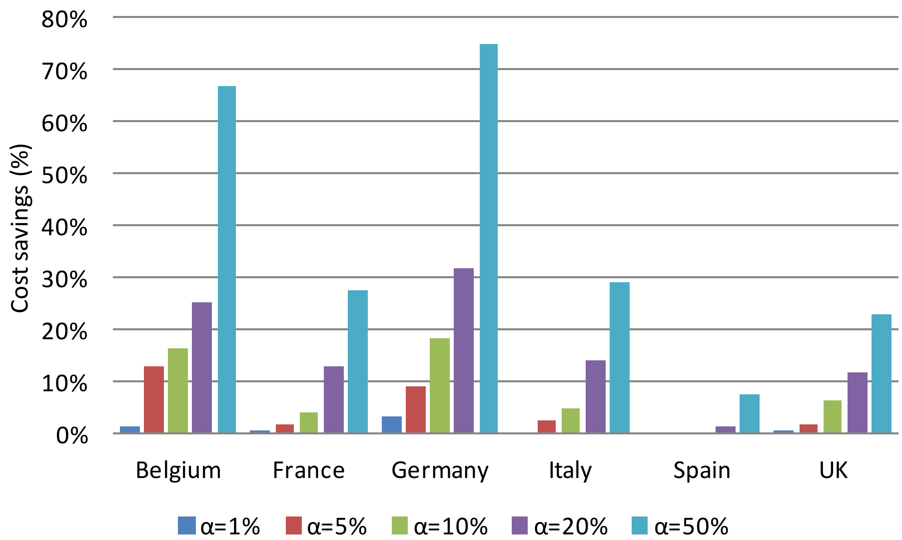

Figure 14: *Electricity distribution cost savings (in %) brought by FID in the 6 target countries of IndustRE for different scenarios of industrial demand flexibility.*

It is observed however that these savings vary significantly among the 6 target countries of the project. Germany is characterized by very high absolute and percentage savings, Spain is characterized by very low absolute and percentage cost savings, and Belgium exhibits low absolute but high percentage savings. In order to explain these results the following factors should be considered:

- Distribution network reinforcements are driven by peak demand levels. As a result, countries with an expected high demand growth towards 2030 exhibit high stress on their distribution networks, which cannot be easily relieved by industrial demand flexibility.

- The value of industrial demand flexibility in reducing peak demand levels depends on the share of industrial demand over the total demand in each country. In other words, a particular value of industrial demand flexibility a is translated in a higher peak demand reduction potential in countries with a higher share of industrial demand and a lower potential in countries with a lower share of industrial demand.
- The absolute costs of distribution network reinforcements and consequently the absolute value of industrial demand flexibility in reducing them depends on the size of the distribution network which is obviously correlated with the size of the country.

Having the above factors in mind, the obtained results can be justified as follows:

- Germany is characterized by the lowest demand growth towards 2030 among the 6 examined countries, according to the Eurostat projections [20]. Furthermore, it is characterized by the highest share of industrial demand among the 6 examined countries (Figure 6). Finally, its large size as a country implies a large size for its distribution network. The combination of these effects justifies why it exhibits the largest absolute and percentage distribution cost savings among the 6 examined countries (Figures 13 and 14).
- Spain is characterized by the highest demand growth towards 2030 among the 6 examined countries [20]. Furthermore, it is characterized by the lowest share of industrial demand among the 6 examined countries (Figure 6). Despite its large size, the combination of these effects justifies why it exhibits the lowest absolute and percentage distribution cost savings among the 6 examined countries (Figures 13 and 14).
- Belgium is characterized by the second lowest demand growth towards 2030, after Germany [20]. Furthermore, it is characterized by the second highest share of industrial demand, after Germany (Figure 6). The combination of these effects justifies why it exhibits the second highest percentage cost savings, after Germany (Figure 14). However, given that Belgium is the smallest country among the 6 examined countries, its absolute cost savings are the second lowest, after Spain (Figure 13).

5. Studies and findings on bottom-up quantification of FID benefits

This chapter presents the examined studies, the data used and the obtained results regarding the bottom-up quantification of FID economic benefits, i.e. the quantification of the electricity cost savings an industrial consumer can achieve by deploying flexibility in its operation.

The industrial consumer examined in these studies is characterized by a yearly demand profile corresponding to an actual typical industrial site in Europe with a peak demand of 2666 kW. This consumer aims at minimizing its total electricity cost by optimally allocating its flexibility across a number of different markets (energy, balancing services, generation / transmission / distribution capacity services).

The objective of Task 5.2 is the quantification of this industrial consumer's electricity cost savings under an "ideal" market framework. In this context, the principles discussed in Section 3.3 are employed in these studies. According to these principles, the prices driving the industrial consumer's actions are determined based on the outcomes of the European power system optimization (presented in Chapter 4).

The above industrial consumer's demand and price data are used by the BUQM model (Section 3.3) to determine the optimal demand adjustments by the industrial consumer minimizing its overall electricity costs. This process is carried out for a number of different scenarios concerning:

- *The extent of flexibility characterizing the examined industrial consumer*: This is expressed by the parameter α_c in this Chapter in order to differentiate it from the extent of flexibility characterizing the rest of the industrial demand in the system. Specifically, the examined scenarios include the values $a\_c = 1\%$, $a\_c = 5\%$, $a\_c = 10\%$, $a\_c = 20\%$, and $a\_c = 50\%$, along with the benchmark scenario $a\_c = 0\%$ which corresponds to a case where the examined industrial consumer does not exhibit any flexibility.
- *The extent of flexibility characterizing the rest of the industrial demand in the system (other than the examined consumer)*: This is expressed by the parameter α_s in this Chapter in order to differentiate it from the extent of flexibility characterizing the examined industrial consumer. Specifically, the examined scenarios include the values $a\_s = 1\%$, $a\_s = 5\%$, $a\_s = 10\%$, $a\_s = 20\%$, and $a\_s = 50\%$.
- *The level of renewable generation penetration in the European system*: Following the analysis in Chapter 4, two alternative scenarios are examined, involving 30% and 60% of the overall electricity consumption in Europe to be supplied by renewable generation sources (*30% RES* and *60% RES* scenarios respectively).
- *The country in which the examined industrial consumer is located*: Six alternative scenarios are investigated in each of which the examined consumer is located in each of the 6 target countries of the project (Belgium, France, Germany, Italy, Spain and United Kingdom).

As demonstrated in Chapter 4, the extent of flexibility characterizing the industrial demand in the system and the level of renewable generation in Europe have a major impact on system investment and operation decisions and therefore affect the prices of energy, balancing and capacity services, based on the pricing principles discussed in Section 3.3.

Furthermore, as also discussed in Section 3.3, energy prices and distribution network capacity prices vary per location. These are the reasons why alternative scenarios for the extent of flexibility characterizing the industrial demand in the system, the level of renewable generation and the country in which the examined industrial consumer is located, are investigated. For each of these scenarios, the differences in the overall electricity cost of the examined industrial consumer between the benchmark scenario $a\_c = 0\%$ (which corresponds to a case where this consumer does not exhibit any flexibility) and each of the scenarios where this consumer exhibits some positive flexibility ($a\_c = 1\%$, $a\_c = 5\%$, $a\_c = 10\%$, $a\_c = 20\%$, and $a\_c = 50\%$) express the cost savings the consumer can achieve by deploying flexibility in its operation.

Figure 15 presents these cost savings (in Euros per year) for a scenario with 30% RES, $a\_s = 10\%$ and different scenarios regarding the examined consumer's flexibility and location. Figure 16 presents the same cost savings as a percentage of the overall electricity costs in the benchmark scenario $a\_c = 0\%$. As expected, higher levels of flexibility (higher values of a_c) increase the total cost savings for the examined consumer, since they enhance its position in energy, balancing and capacity markets.

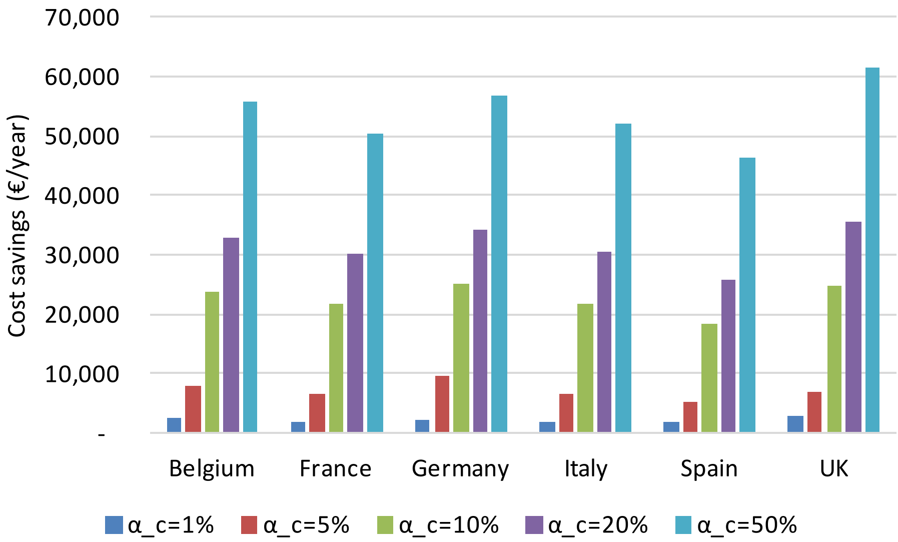

Figure 15: *Total cost savings (in €/year) achieved by the examined industrial consumer for a scenario with 30% RES, $a\_s = 10\%$ and different scenarios regarding its extent of flexibility and its location.*

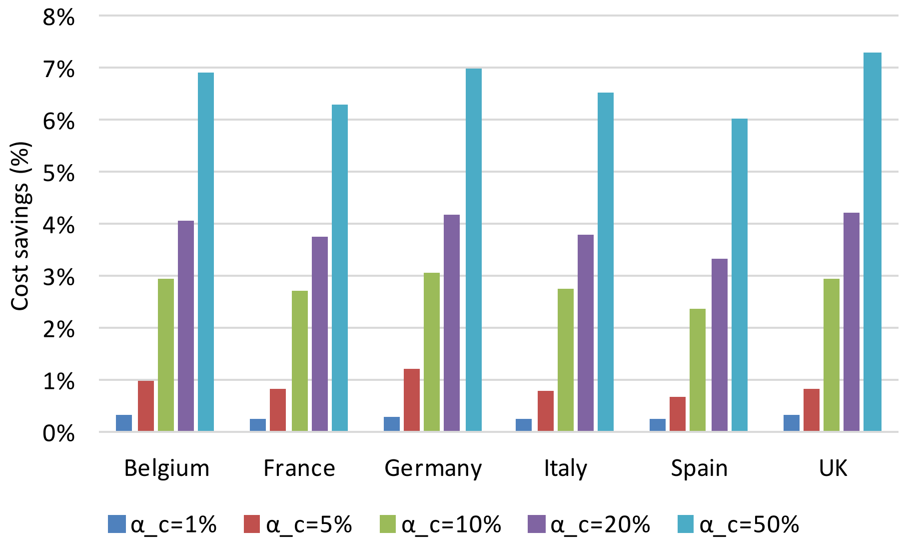

Figure 16: *Total cost savings (in %) achieved by the examined industrial consumer for a scenario with 30% RES,* $a\_s = 10\%$ *and different scenarios regarding its extent of flexibility and its location.*

Figures 17 and 18 present the same absolute and percentage cost savings but considering now a 60% RES scenario. By comparing these savings with the respective savings of Figures 15 and 16 it is concluded that the cost savings for each of the examined consumer's flexibility and location scenarios are significantly higher under a higher penetration of renewable generation in the system. This result is to be expected given that the same trend applies to the system cost savings brought by FID (as demonstrated in Figure 7, Chapter 4) and demonstrates the synergy between increased penetration of renewable generation and the profitability of flexibility deployment by industrial consumers, which constitutes a fundamental result of the IndustRE project.

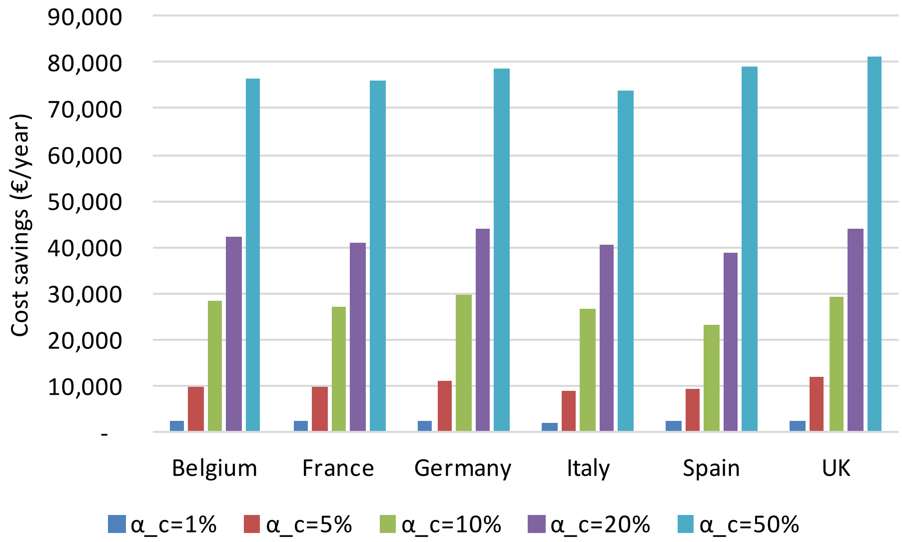

Figure 17: *Total cost savings (in €/year) achieved by the examined industrial consumer for a scenario with 60% RES,* $a\_s = 10\%$ *and different scenarios regarding its extent of flexibility and its location.*

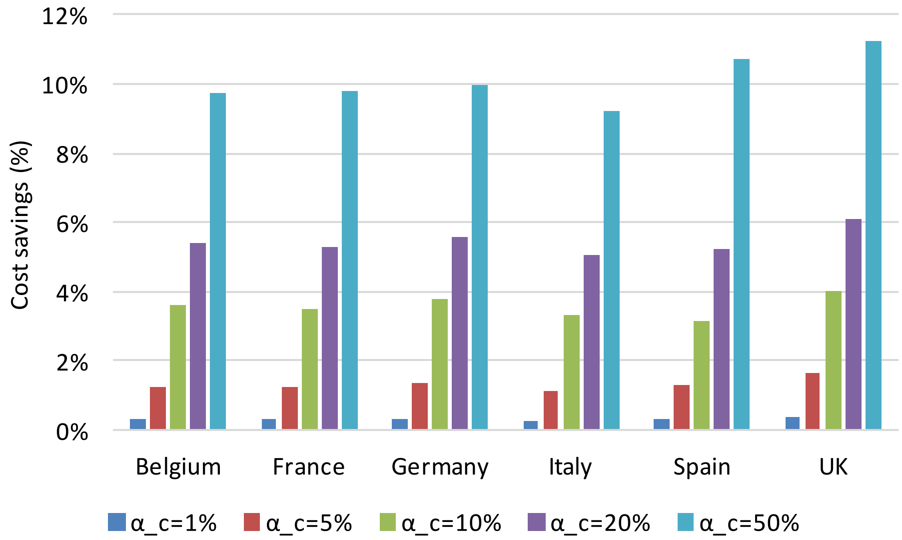

Figure 18: *Total cost savings (in %) achieved by the examined industrial consumer for a scenario with 60% RES,* $a\_s = 10\%$ *and different scenarios regarding its extent of flexibility and its location.*

Figures 19-22 present the absolute and percentage cost savings for a fixed scenario of $a\_c = 10\%$ for the examined consumer's flexibility and different scenarios regarding the flexibility characterizing the rest of the industrial demand in the system (other than the examined consumer) and the location of the examined consumer. Figures 19 and 20 correspond to a 30% RES scenario while Figures 21 and 22 correspond to a 60% RES scenario. The cost savings achieved by the examined consumer are reduced as the flexibility of other industrial consumers in the system is increased. This result is justified by the fact that the examined consumer faces increased competition by other industrial consumers in the energy, balancing and capacity markets, reducing the profitability of the services it provides to the system.

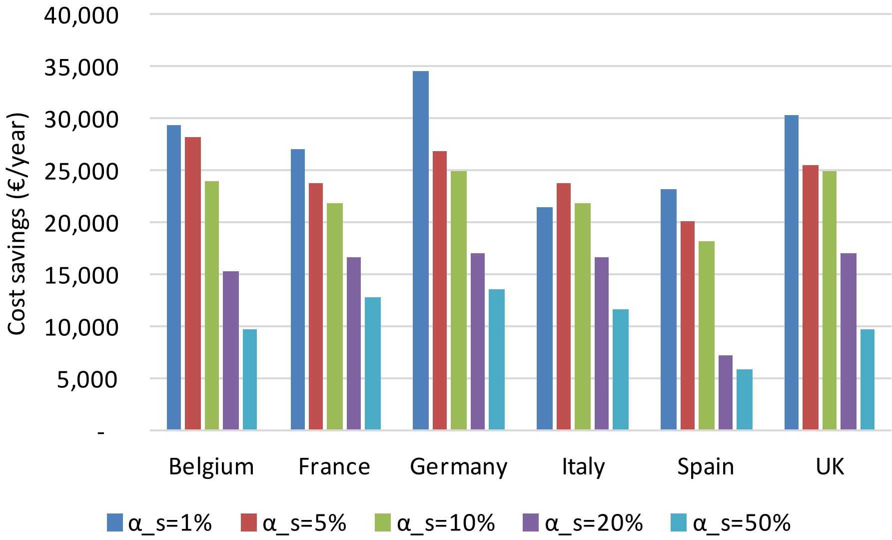

Figure 19: *Total cost savings (in €/year) achieved by the examined industrial consumer for a scenario with 30% RES,* $a\_c = 10\%$ *and different scenarios regarding its location and the extent of flexibility characterizing the rest of the industrial demand in the system.*

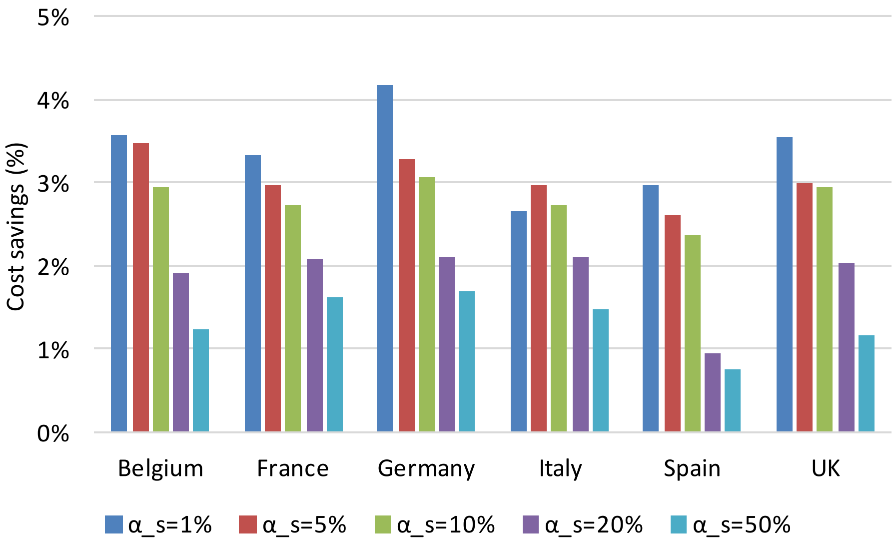

Figure 20: *Total cost savings (in %) achieved by the examined industrial consumer for a scenario with 30% RES,* $a\_c = 10\%$ *and different scenarios regarding its location and the extent of flexibility characterizing the rest of the industrial demand in the system.*

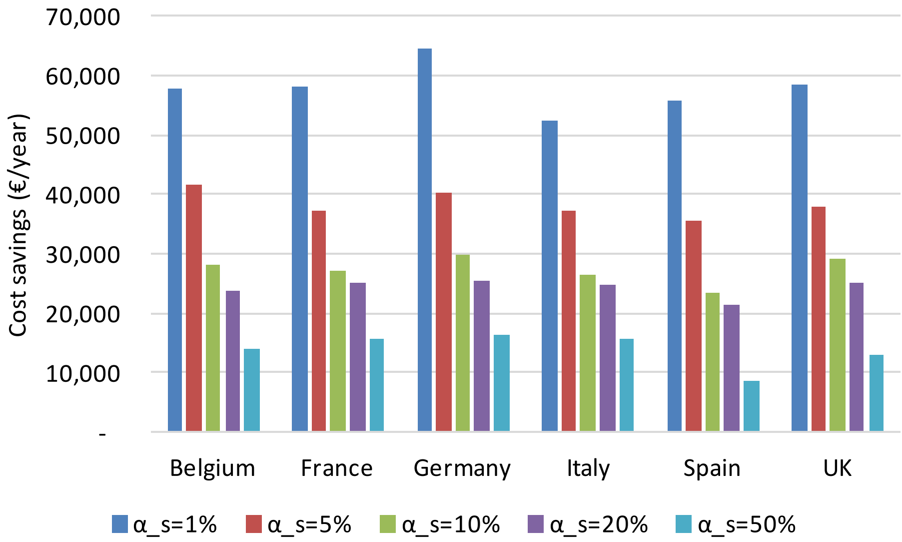

Figure 21: *Total cost savings (in €/year) achieved by the examined industrial consumer for a scenario with 60% RES,* $a\_c = 10\%$ *and different scenarios regarding its location and the extent of flexibility characterizing the rest of the industrial demand in the system.*

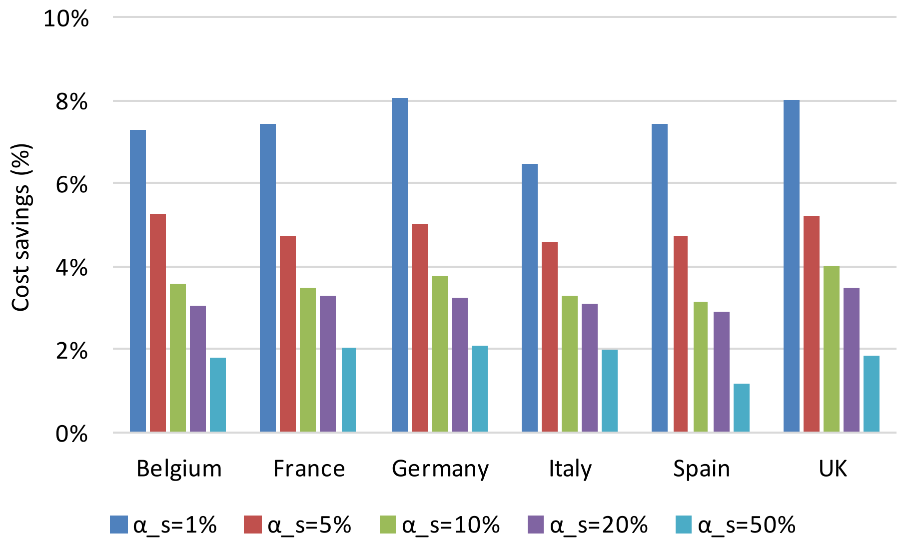

Figure 22: *Total cost savings (in %) achieved by the examined industrial consumer for a scenario with 60% RES,* $a\_c = 10\%$ *and different scenarios regarding its location and the extent of flexibility characterizing the rest of the industrial demand in the system.*

Figures 23 and 24 break down the total cost savings to the different value streams accessed by the consumer and discussed in Section 3.3, for a scenario with $a\_c = 10\%$, $a\_s = 10\%$ and different scenarios regarding the location of the consumer. Figure 23 corresponds to a 30% RES scenario while Figure 24 corresponds to a 60% RES scenario. These values streams include:

- ***Energy cost savings*** (denoted in dark blue colour)

- ***Revenues from provision of balancing services*** (denoted in red colour)
- ***Revenues from provision of generation capacity services*** (denoted in green colour)
- ***Revenues from provision of transmission capacity services*** (denoted in light blue colour)
- ***Revenues from provision of distribution capacity services*** (denoted in purple colour)

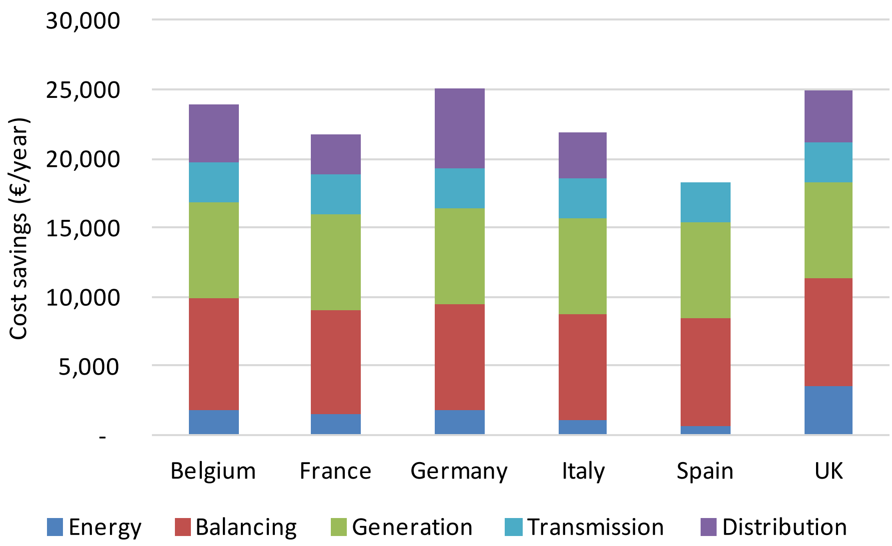

Figure 23: *Break-down of cost savings (in €/year) achieved by the examined industrial consumer for a scenario with 30% RES,* $a\_c = 10\%$ *,* $a\_s = 10\%$ *and different scenarios regarding its location.*

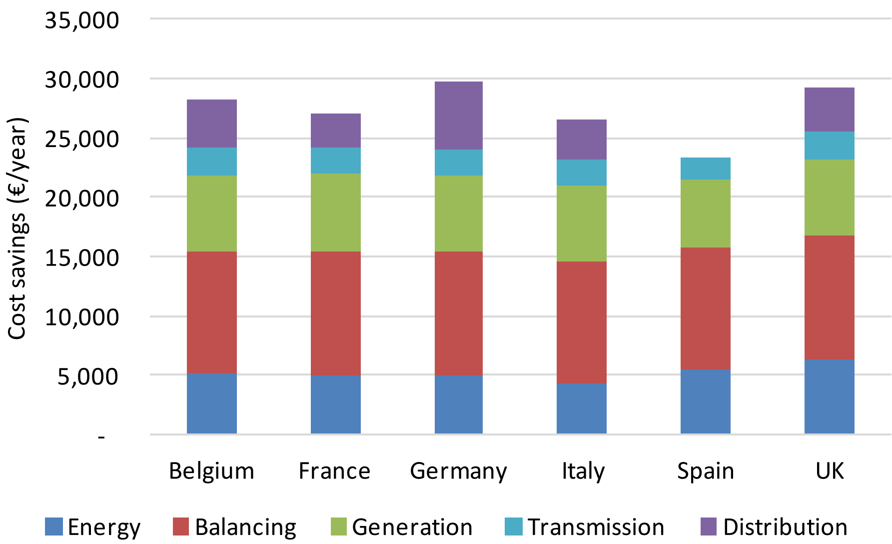

Figure 24: *Break-down of cost savings (in €/year) achieved by the examined industrial consumer for a scenario with 60% RES,* $a\_c = 10\%$ *,* $a\_s = 10\%$ *and different scenarios regarding its location.*

Finally, the comparison between the different scenarios regarding the location of the examined consumer yields the following conclusions:

- In most of the examined scenarios the consumer achieves the highest cost savings in the case it is located either in Germany or in the UK. In the case of Germany, this result is driven by the fact that the consumer makes the highest revenues from the provision of distribution capacity services (Figures 23-24), which is in turn justified by the fact that Germany exhibits the highest distribution network cost savings by the deployment of industrial demand flexibility, as demonstrated in Figure 13. In the case of the UK, this result is driven by the fact that the consumer achieves the highest cost savings in the energy market (Figures 23-24), which is in turn justified by the fact that the UK has limited interconnections with other countries and limited amount of flexible generation units.
- In most of the examined scenarios the consumer achieves the lowest cost savings in the case it is located either in Italy or in Spain. In the case of Italy, this result is justified by the fact that the consumer achieves low cost savings in the energy market (especially in the 60% RES scenario – Figure 24), which is in turn justified by the fact that Italy has a significant amount of flexible generation units (mainly hydro generation). The same factor applies in the case of Spain (especially in the 30% RES scenario – Figure 23), but also the consumer makes the lowest revenues from the provision of distribution capacity services (Figures 23-24), which is in turn justified by the fact that Spain exhibits the lowest distribution network cost savings by the deployment of industrial demand flexibility, as demonstrated in Figure 13.

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