Preparatory study
on Smart Appliances

Task 6

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LIST OF ACRONYMS

AC	Air Conditioning
ADSL	Asymmetric Digital Subscriber Line
BAT	Best Available Technology
BRP	Balancing Responsible Parties
CFL	compact fluorescent light
CHP	Combined Heat and Power
DHW	Domestic Hot Water
DOCSIS	Data Over Cable Service Interface Specification
DR	Demand response
DSF	Demand Side Flexibility
DSO	Distribution System Operators
ESCO	Energy Service Company
ETSI	European Telecommunications Standards Institute
EV	Electric vehicle
GLS	general lighting service 'incandescent'
GSM	Global System for Mobile Communications
GW	gigawatt
HEG	Home Energy Gateway
HID	high intensity discharge lamp
HVAC	Heating, Ventilation and Air Conditioning
LED	light emitting diode
LFL	linear fluorescent lamp
LTE	3GPP Long Term Evolution (4G)
M2M	Machine to Machine
NRVU	Non-Residential Ventilation Units
PLC	power line communication
PV	Photovoltaic
RES	Renewable Energy Sources
RVU	Residential Ventilation Units
SAREF	Smart Appliances REFerence ontology
SOC	State Of Charge
TSO	Transmission System Operators
TWh	Terawatt hour
UMTS	Universal Mobile Telecommunications System
UPS	Uninterruptible power supply
VDSL	Very-high-bitrate Digital Subscriber Line
VRF	variable refrigerant flow

TASK 6 ENVIRONMENT & ECONOMICS

Following the MEErP Methodology for Energy related products, the scope of Task 6 consists of the identification of the identified (aggregated clusters of) design options, their monetary consequences in terms of Life Cycle Costs for the consumer, their environmental costs and benefits and pinpointing the solution with the least Life Cycle Costs (LLCC) and the Best Available Technology (BAT) compared to the base-cases described in Task 5. The comparison of the Life Cycle Costs and the environmental costs and benefits should be done for the design options using the same approach as was done for the base-cases.

As explained in the introduction of Task 5, the approach taken in this Lot 33 Preparatory Study is slightly different, as it specifically addresses the implications underlying the connectivity and demand side flexibility (DSF) functionality aspect horizontally over a large group of various products. This implies that the DSF functionality will have implications on the level of the individual product and the network in which the product functions (see Task 4). Besides this individual product level, the aggregated DSF which potentially can be provided by a group of smart appliances also gives rise to environmental and economic benefits which can be found at the level of the entire energy system. If the study would be limited to the usual MEErP base-case environmental and economic impact data, these system impacts would be kept out of consideration.

In this context, the Task 6 report of this Lot 33 Preparatory Study mainly focuses on the assessment of the economic and environmental benefits which the use of flexibility from smart appliances can have for the use cases defined in Task 2 (day-ahead use case and imbalance use case). In this Task 6 report it is investigated how potential (future) flexibility provided by smart appliances can support the power system and an attempt is made to quantify the value of the economic and environmental benefits potentially provided by the flexibility of smart appliances to the energy system.

The benefits of flexibility from smart appliances are evaluated according to the three key performance indicators (KPIs) already defined in Task 5: CO_2 emission savings, impact on the utilized generation mix in terms of efficiency (which indirectly shows how many more Renewable Energy Sources (RES) can be integrated in the system) and impact on the total energy system costs and marginal energy prices. The resulting KPIs are compared with the KPIs calculated in task 5 for the base case. Where the base-case scenario served as a reference situation which did not take into account flexibility, in this Task 6 report the KPIs are calculated for a situation in which a certain share of smart appliances (based on Task 2), each with their flexibility profile (based on task 3), could provide flexibility to the system in the future.

The value of the benefits provided by the flexibility of smart appliances to the system is extracted from the computed KPIs in tasks 5 and 6. It is expressed in environmental and economic terms for the day-ahead market use case and for the imbalance use case. The obtained value for the day ahead use case is the highest value that can be obtained, as the perfect foresight is assumed, all the flexibility is utilized in a holistic aggregated way to benefit the system, and no control imperfections, such as communication delay, suboptimal controller tuning, etc. exist.

It is of interest to compare the economic value from flexibility provided by smart appliances to the power system with the costs related to the smart appliances providing flexibility. Although it is not feasible in the context of this Preparatory study to make a full cost-benefit analysis, the comparison of the costs and benefits for the system with the additional costs and benefits for the end-user and manufacturer bring some perspective in the derived values.

The task 6 report is structured as follows: section 6.1 gives an overview of the developed flexibility model and the different assumptions taken. Next, section 6.2**Error! Reference source not found.** lists the data assumptions and sources utilized in this task. In section 6.3, the results of the optimisation model are discussed for the selected use cases. Section 6.4 evaluates the costs against the benefits of flexibility from smart appliances.

6.1. ASSESSMENT MODEL DESCRIPTION

In task 5, the optimisation tool and model are described that allow simulating the behaviour of the energy system for the entire EU28. In order to analyse how smart appliances could support the energy system for different use cases (day ahead use case and imbalance use case), a first step to be taken is identification of the type of flexibility from smart appliances that is available. For instance, flexibility can be identified as load shifting, load shedding, storage, etc. Once the flexibility type is identified, it is possible to develop an additional flexibility model and incorporate it in the power system model presented in Task 5.

The identification of flexibility type per smart appliance group, and the accompanying developed flexibility model are described in this section in more detail.

The outcomes of Task 1 were used to define the categories of smart appliances with sufficient flexibility potential. For each of these categories, the flexibility potential was determined.

The following categories of appliances were identified as appliances with high potential, and, hence, are considered further in this task:

1. Periodical appliances (Dishwashers, Washing machines, and Tumble dryers),
2. Energy storing appliances (Refrigerators and freezers, and storage water heaters, for residential and commercial purposes),
3. HVAC heating in residential and tertiary buildings (electric heating),
4. HVAC cooling in residential and tertiary buildings (air conditioning),
5. Residential energy storage system (home batteries),
6. Tertiary cooling or commercial refrigeration,

Washer-dryers, which belong to the periodical appliances group, were also identified to have potential for flexibility provision. Nevertheless, they are omitted from further consideration in this task due to relatively small amounts throughout the EU-28 area, and a lack of data in terms of hourly profiles, and average maximal shifting period.

The flexibility or demand response potential of each category of smart appliances is defined by two parameters:

- **The energy shifting potential** = the amount of energy that can be shifted, expressed in [MWh/h], i.e. what is the maximum consumption of a group of smart appliances that could be consumed at a different moment in time. The energy shifting potential is based on an hourly flexibility profile.
- **Average maximal shifting period =** the maximum number of hours [h] that the demand of the appliance can be shifted, i.e. how much later/earlier should take consumption by the smart appliances take place, compared to the initially planned time.

The flexibility model is determined based on the outcome of Task 3. The flexibility potential per category was used to model the hourly amount of available flexibility and its shifting potential. The hourly flexibility profiles reported in Task 3 are utilized to represent the shifting potential. This amount of flexibility can be shifted by the corresponding shifting potential given in hours.

Additionally, in the energy shifting potential, the following aspects are covered:

- Seasonality: the seasonal effects in availability of flexibility from smart appliances are considered for the appliances of which the energy utilization depends on the seasons. As discussed in Task 3, there is no difference in average consumption profile for e.g., dishwashers, washing machines, refrigerators and freezers.
- Climatic zone: the effects on the amount of flexibility from smart appliances due to the different climatic zones are considered for the appliances of which the energy utilization depends on the climatic zone, in particular, outside temperature, radiation levels etc. The methodology to take these effects into account was discussed in Task 3 for residential heating and cooling, tertiary heating and cooling, and commercial refrigeration groups.
- Time zone: Hourly flexibility profiles of countries in different time zones are shifted to match with the model time zone[1].

The seasonality and climatic zone aspects are not relevant for all the groups of smart appliances. For these groups, no such patterns are contained in the energy shifting potential profiles. Nevertheless, for the appliances from residential heating and cooling, tertiary heating and cooling, and commercial refrigeration, these aspects are relevant and hence included in the hourly profiles of energy shifting potential.

Besides constraints on the shifting potential and shifting period, additional constraints are also taken into account for some groups of smart appliances, such as:

- **Rebound constraints.** A shift in demand means that the consumption is reduced at a certain moment in time and transferred to another period of time, where an increase in scheduled consumption can be seen. This is often referred to in literature as rebound effect. Note that there is no reduction in total consumption, nor increase in total consumption due to flexible operation; there is only shifting of demand to consume at a more appropriate moment. The rebound effect is valid for all the considered groups of flexible smart appliances. Hence, this constraint is added to all the flexibility models[2].
- **Additional technical constraints.** For example, utilization of flexibility from residential and tertiary HVAC appliances should be limited to avoid loss of comfort. Once the flexible consumption is shifted, it cannot be shifted again for a given amount of time to allow for recuperation of ambient temperature. Therefore, additional technical constraints are added to limit the use of flexibility in the hours to come after the initial utilization of flexibility. In the model, the time needed to set back the temperature after flexibility utilization is set to be 6 hours.

Home batteries are modelled as storage appliances, and hence not as demand shifting. The first order storage model of given efficiency is chosen to represent the home batteries.

[1] The model time zone is chosen to be GMT+1. The same results would have been obtained for any choice of the model time zone.

[2] With the exception of residential energy storage system, as this group is not modelled as demand shifting.

To summarize, the flexibility models are mapped to the smart appliance groups as follows:

- First order storage model with losses: home batteries.
- Demand shifting: periodical appliances (washing machines, dishwashers, tumble dryers), energy storing appliances (residential refrigerators and freezers, electric storage water heaters), commercial refrigeration.
- Demand shifting with minimum down time constraint: Residential heating and cooling, tertiary heating and cooling.

The developed optimisation model determines the optimal utilization of flexibility from each appliance group so that the total system costs are minimized, and taking into account the constraints on flexibility as defined above.

The computed benefits for the day-ahead use case give the upper boundary of the flexibility impact, as the flexibility is used in the optimal way assuming that the renewable generation power profiles of wind and solar power plants, and the demand profile are perfectly known in advance. However, on the other hand, some assumptions on flexibility from smart appliances may be considered conservative thus underestimating the economic value of the flexibility. For instance, firstly, the assumption taken on the flexibility shifting times may be considered conservative for some appliance categories (e.g. 3 hours for periodical appliances), and secondly, the assumption may be conservative that residential and tertiary buildings have a low thermal inertia, which led to the introduction of additional assumption on the recuperation, or minimum down time. Nevertheless, these assumptions are chosen to mimic the business-as-usual case, i.e., the situation in which there are no additional policy approaches and incentives for the end-users to operate the appliances in a smart grid way. The impact of the effects of changes in these assumptions will be treated later in Task 7.

The KPIs are defined on the system level, and as such, they quantify the operation of the system as a whole using the flexibility of all the smart appliances together. Therefore, KPIs cannot be determined separately per smart appliances category. This means that no distinction in resulting benefits from flexibility is made between smart appliance groups. Nevertheless, optimal schedule of different flexibility models (storage, demand shifting, and demand shifting with minimum down time constraint) can be extracted from the model. Of course, not only benefits but also the different costs of smart appliances to exploit the flexibility potential have to be taken into account. Costs are specific to each type of appliance. The cost perspective is further discussed in section 6.4.

6.2. ASSESSMENT DATA

In this section, an overview of the data used related to the developed flexibility model of smart appliances is given. Wherever possible, it is only referred to a previous task where the data is collected or generated. Herein, only the numbers and figures that were not presented in one of the previous tasks are given.

6.2.1. NUMBER OF SMART ENABLED APPLIANCES

The utilized model is the zonal model of the interconnected EU-28 area. Therefore, among others, the model utilizes as inputs the following hourly profiles:

- hourly profiles of total demand,
- hourly profiles of wind and solar power production, and
- hourly profiles of profiles of flexibility (per flexibility group)

for each EU-28 member state. To calculate the total amount of available flexibility for each category of smart appliances in each country of EU 28, the numbers of smart enabled appliances in each country for 2014, 2020 and 2030 are needed.

The number of smart enabled appliances is calculated by multiplying the percentage (%) of smart enabled appliances, as described in task 2, with the number of households in each country of EU 28. The table below gives an overview of the % of smart enabled appliances and is fully based on findings presented in task 2.

Table 1 Percentage of smart enabled appliances per benchmark year

Smart enabled appliances		2014	2020	2030
Periodical appliances	Dishwashers	0%	2%	8%
	Washing machines	0%	1%	4%
	Tumble dryers	0%	2%	16%
Energy storing appliances	Refrigerators and freezers (residential)	0%	5%	20%
	Electric storage water heaters	0%	5%	20%
Residential heating and cooling	HVAC residential cooling (heat pump)	5%	18%	54%
	HVAC residential heat pump heating	5%	18%	54%
	HVAC residential Joule heating	0%	3%	21%
Tertiary heating and cooling	HVAC tertiary cooling (heat pump)	5%	18%	54%
	HVAC tertiary heat pump heating	5%	18%	54%
	HVAC tertiary Joule heating	0%	3%	21%
Commercial refrigeration	Tertiary cooling (evaporator, compressor)	0%	10%	50%

For later convenience, on basis of the data and results from tasks 1 – 3, and on basis of the described demand flexibility modelling approach, here we define the following four groups of smart appliances:

- Group 0: residential storage appliances (home batteries)
- Group 1: periodical appliances (dishwashers, washing machines, tumble dryers). This group can be shift consumption flexibly for 3 hours.
- Group 2: energy storing appliances and commercial refrigeration (residential refrigerators and freezers, electric storage water heaters, and tertiary refrigerators and freezers (tertiary cooling). This group can be shifted for 1 hour (or less).
- Group 3: residential and tertiary cooling and heating, all technologies. This group can be shifted for 1 hour, however, once a part of the flexible consumption is shifted, there should be a recuperation time of 6 hours to avoid loss of comfort.

Table 2 gives an overview of the number of households in each EU28 country for 2014. The data on number of households per EU-28 member state is obtained from the EU-28 population data for

2014[3], and average household size per EU-28 country[4], which are both downloaded from Eurostat data portal[5].

To determine the share of the number of households in each EU28 country for 2020 and 2030, trends in population shares for each of EU28 countries were assessed over the last decade were assessed. Data from 1994 until now with the population size per country is downloaded from Eurostat data portal, and from this data, the population shares in the total EU-28 population per country and year are computed. These shares are presented in Figure 1. On horizontal axis, the years are given, from 1994 until 2014. On vertical axis, share in the total EU-28 population per country is given as a percentage. For each country, there is a line that represents the trend in its share in total EU-28 population over the last ten years.

In Figure 1, it can be observed that besides the slight decrease in population of Germany (top brown curve), Poland and Romania, and slight increase in population of Spain (green curve), France, and United Kingdom, the population shares remained constant over the last 10 years. Therefore, it is reasonable to assume that the share of the population and the number of households in each EU28 country in 2020 and 2030 will remain constant over the years to come, i.e., the same as in 2014.

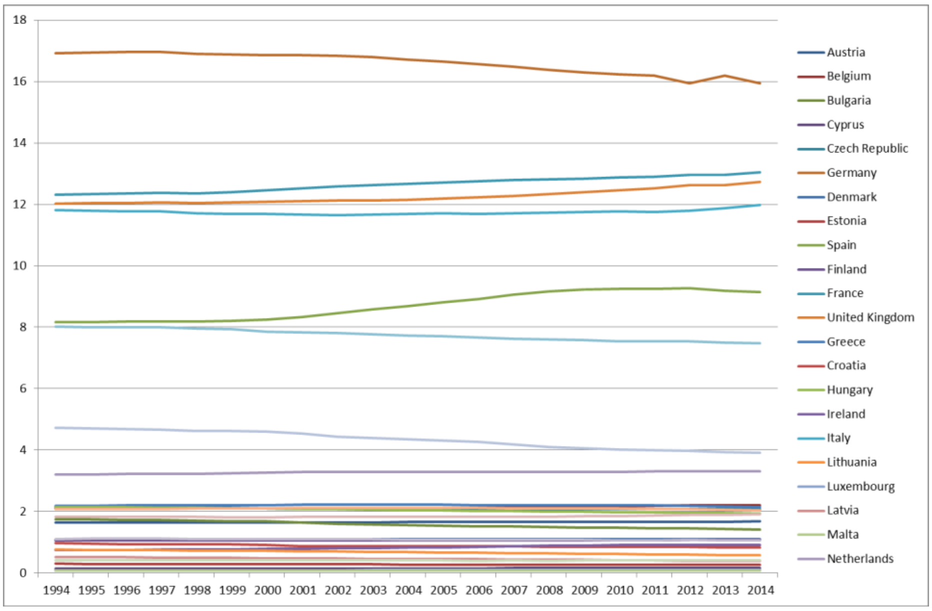

Figure 1 Trend in population share per EU-28 member state over the last decade, own compilation, data source: Eurostat web portal. Population share is defined as share of population of EU-28 member state in the total EU-28 population, and is expressed in %.

[3]See http://ec.europa.eu/eurostat/statistics-explained/index.php/Population_and_population_change_statistics

[4]http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Average_household_size,_2014_(average_number_of_persons_in_private_households).png

[5] http://appsso.eurostat.ec.europa.eu/nui/setupDownloads.do

Table 2 Number of households per EU-28 member state in 2014, and the share of households per member state in the total number of households in EU-28 area, source: own computation on basis of data from Eurostat data portal[6]

EU-28 member	Number of households	% households
Austria	3882534	1,75
Belgium	4679672	2,11
Bulgaria	3009974	1,36
Cyprus	315742	0,14
Czech Republic	4576238	2,07
Germany (including former GDR)	40491250	18,28
Denmark	2687369	1,21
Estonia	597521	0,27
Spain	18592353	8,39
Finland	2600720	1,17
France	30119230	13,60
United Kingdom	28092678	12,68
Greece	4538505	2,05
Croatia	1512880	0,68
Hungary	4289769	1,94
Ireland	1710083	0,77
Italy	26430061	11,93
Lithuania	1332894	0,60
Luxembourg	231800	0,10
Latvia	830743	0,38
Malta	158283	0,07
Netherlands	7665913	3,46
Poland	14078420	6,36
Portugal	4000409	1,81
Romania	7373696	3,33
Sweden	4848055	2,19
Slovenia	859158	0,39
Slovakia	2006907	0,91

[6] http://ec.europa.eu/eurostat/statistics-explained/index.php/Population_and_population_change_statistics and http://appsso.eurostat.ec.europa.eu/nui/setupDownloads.do and http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Average_household_size,_2014_(average_number_of_persons_in_private_households).png

6.2.3. NUMBER OF RESIDENTIAL STORAGE APPLIANCES (HOME BATTERIES)

For residential storage appliances, under which we understand home batteries for the purposes of this study, the significant number of home batteries is assumed to be present only in Germany, as today, in no other countries, the investment of home batteries is subsidized[7]. The numbers are taken from the same market study, and are presented in Table 3.

The aggregated energy capacity of the batteries is given under the column energy capacity and is expressed in MWh. The charging rate, which corresponds to the maximal input and output charging power, are given in the column “charging rate”. Lastly, the electricity-to-electricity efficiency factor is given in the most right column of the table.

Table 3 Installed energy capacity of home batteries (only for Germany), source: B. Normark et al, “How can batteries support the EU electricity network?”, technical report, 2014

Year	Charging rate [MWh/h]	Energy capacity [MWh]	Efficiency η [%]	Number
2014	16,83	43,0	85	6000
2020	25,25	64,5	85	9000
2030	42,08	107,5	85	15000

6.2.4. FLEXIBILITY PROFILE

In task 3, the relevant parameters to determine the aggregated flexibility potential of smart appliances are described. These profiles are utilized in this task, and not repeated in the text of this report.

6.2.5. ASSUMPTIONS

In this section, an overview of assumptions related to the flexibility of smart appliances is presented. Note that the assumptions below are both based on reflections made in earlier tasks and additional assumptions made in task 6.

1. The optimisation model used is the model as explained in task 5. It determines the value of flexibility for each individual EU28 country, taking into account that:
    a. Import and export between countries is possible, but constrained by the capacity of the transmission lines.
    b. There are different time zones between countries

2. The flexibility of smart appliances is modelled as three different large groups:
    a. load shifting, for periodical appliances (washing machines, dishwashers, tumble dryers), energy storing appliances (residential refrigerators and freezers, electric storage water heaters), and commercial refrigeration;

7 B. Normark et al, “How can batteries support the EU electricity network?”, technical report, 2014, http://www.insightenergy.org/ckeditor_assets/attachments/48/pr1.pdf

   b. load shifting with additional constraints on minimum down (recuperation time): residential heating and cooling, tertiary heating and cooling; and
   c. storage: home batteries

3. The price to activate flexibility from smart appliances is set at zero in the model, to allow determining the maximum potential and evaluate the maximal benefits of smart appliances.

4. For a certain category of smart appliances, in case the flexibility has the same characteristics (same shifting period), the smart appliances are considered of equal value for the energy system. This means that for example, no distinction is made in the model between washing machines and dish washers. In section 6.4, it will be further explained that although benefits could be considered similar for certain appliances, differences in costs could still result in a preference for one type of appliance to provide flexibility.

5. The total amount of flexibility is based on the assumption that on average, there is one appliance per household, meaning that in order to calculate the entire base of smart enabled appliances, it is sufficient to multiply the % of smart enabled appliances (data provided in task 2) with the number of households for a certain country. This methodology was used for periodical appliances and energy storing appliances.

6. EVs and possible flexibility from EVs is not represented in the model. Also flexibility coming from industrial demand response is not taken into account in the model. This means that the value of flexibility to be awarded to smart appliances is slightly overestimated, as a part of the need for flexibility could be covered by industrial demand response or EVs instead of smart appliances. Today, it is unclear which business case will be most profitable to offer flexibility (industrial demand response, EVs, smart appliances). It will depend on both, the costs to enable this flexibility (including infrastructure, communication technology,…), and the characteristics of the flexibility (reaction time, availability,…).

7. For home batteries, it is assumed that only in Germany, this market will develop in the scope 2020 and 2030, due to the fact that today, in no other countries, the investment of home batteries is subsidized[8].

6.2.6. Computation of KPIs

The economic and environmental benefits of smart appliances from an energy system perspective are quantified by means of the following key performance indicators (KPIs), as defined for the base case in Task 5.

1. KPI1: Economic value in terms of total energy system costs. This KPI quantifies the avoided costs related to the more efficient use of the energy system following the achieved flexibility.
2. KPI2: Total amount of CO_2 emissions over the considered period. This KPI quantifies part of the environmental benefits of decreased utilization of the less efficient and more CO_2 emitting peaking power plants in the system.
3. KPI3: Energy efficiency of the utilized generation mix over the considered period. This KPI more specifically indicates the increased share of Renewable Energy Sources (RES) integrated in the generation mix, and decrease in utilization of low efficient, often peaking, generating units. Energy efficiency of the utilized generation mix as defined here is related to the

[8] http://www.insightenergy.org/ckeditor_assets/attachments/48/pr1.pdf

primary energy savings in the electricity production. It is not related to e.g. decrease in total consumption due to more efficient energy utilization.

For the flexibility case, the KPIs are computed in the same way as presented in task 5, with the exception of the KPI2 (CO_2 emissions) in the imbalance use case.

In the base case, to compute the KPI 2, i.e., the CO_2 emissions, in the imbalance use case, we define the generation mix that balances the system as the difference in the generation mix between the day-ahead and the imbalance use case. KPI2 value is obtained by multiplication of emission factor per technology, the change in generation production per technology, and the hourly imbalance volumes of each EU-28 member state.

Herein, the assumption is that as large part of the imbalance volume as possible is resolved by utilization of smart appliances flexibility. The remaining imbalance volume (if any) is assumed to be covered by the generation side. As the imbalance case is an extended case of the day-ahead use case, and as it is modelled by running the unit commitment model once again, the volume by which the smart appliances contribute to the balancing is computed as a difference between the baseline flexibility and the optimally scheduled flexibility. Similarly, the remaining volume is covered by the differences in generation between the day-ahead and imbalance use case schedule.

Finally, to compute the KPI2, the imbalance volumes that were balanced by the flexibility of smart appliances are assigned with the emission factor 0, and the remaining is assigned by the corresponding generation type emissions factor, see Table 4 in Task 5.

Given this definition of KPI2, it can be interpreted as the additional CO_2 emissions that were emitted or saved due to the balancing actions. In this sense, the emissions from the day-ahead use case are not taken into account in this KPI2 definition. Note that by definition, KPI2 can be negative. If it is negative, the total system CO_2 emissions after balancing actions are lower than the computed CO_2 emissions from the day-ahead market use case.

6.3. FLEXIBLE CASE

In this section, the results of the KPI calculation are described for the two selected use cases: day ahead use case and imbalance use case. In addition, the results are compared with the KPIs calculated for the benchmark case in task 5.

Same as in Task 5, for each of the three chosen benchmark years: 2014, 2020, and 2030, the model is run over a time horizon of one year. The KPIs represent the yearly values: KPI1 are the yearly electrical energy production costs, KPI2 are the yearly CO_2 emission quantities from the generation mix utilized to produce electricity, and KPI3 is the efficiency of the utilized generation mix throughout the whole year, which is defined as the quotient of the produced electrical energy and the total primary energy utilized to produce the electrical energy.

6.3.2. DAY-AHEAD USE CASE

In Table 4, KPIs for the day-ahead use case with flexibility from smart appliances are presented. The same trends over the benchmark years that were observed in the base case can be seen here:

- there is an increase in total costs over the years, which is largely due to the increased fuel and in particular increased CO2 emission costs
- there is a decrease in CO2 emissions over the years, which is largely due to the increased installed capacity of RES
- there is an increase in generation mix efficiency, which is due to the increased installed capacity of RES.

All the observations reported in Task 5 still hold. In the table, it can be seen that the numbers for KPI3 are very similar to those presented in Task 5. These KPIs are the most interesting when put in perspective with the KPIs computed for the base case. The analysis of these differences is presented below, after a short discussion on the effects of flexibility on the residual load curve.

Table 4 KPIs for the day-ahead use case for each of the benchmark years

Day ahead use case	KPI1 (total system costs) [M€]	KPI2 (CO_2 emissions) [Mt]	KPI3 (efficiency of the utilized generation mix) [%]
2014	63.604,8	803,24	54,37
2020	75.024,7	735,43	58,16
2030	113.793,8	694,72	61,34

→ **Effects of flexibility**

Residual load curve is determined as the difference in total demand and total production of intermittent, non-dispatchable renewable energy sources. It is in fact the remaining load that has to be satisfied by the production of dispatchable generation. The residual load curve is of the same resolution as the original profiles, i.e., it is an hourly curve. It has been observed that the lowest total system generation costs are obtained for flat residual demand curves, (Matek and Gawell, 2015). Therefore, it is expected that the optimal utilization of the flexibility from smart appliances will result in a residual curve with lower peak (minimum and maximum values), and of lower volatility, i.e. of smoother nature.

In Figure 2, effects of utilization of flexibility on the residual demand curve are shown for the 2030 scenario, in which there was the most of smart appliances flexibility available (compared to other benchmark years). A week in winter, in particular, the second week in 2030, is shown in the figure. In red, the base scheduled demand is shown, without utilization of flexibility, and in black the optimized demand with the utilization of flexibility from smart appliances, coming from the flexible case. The residual demand curve is shown for the aggregated EU-28 area, but individual residual curves of each EU-28 member state show the similar patterns.

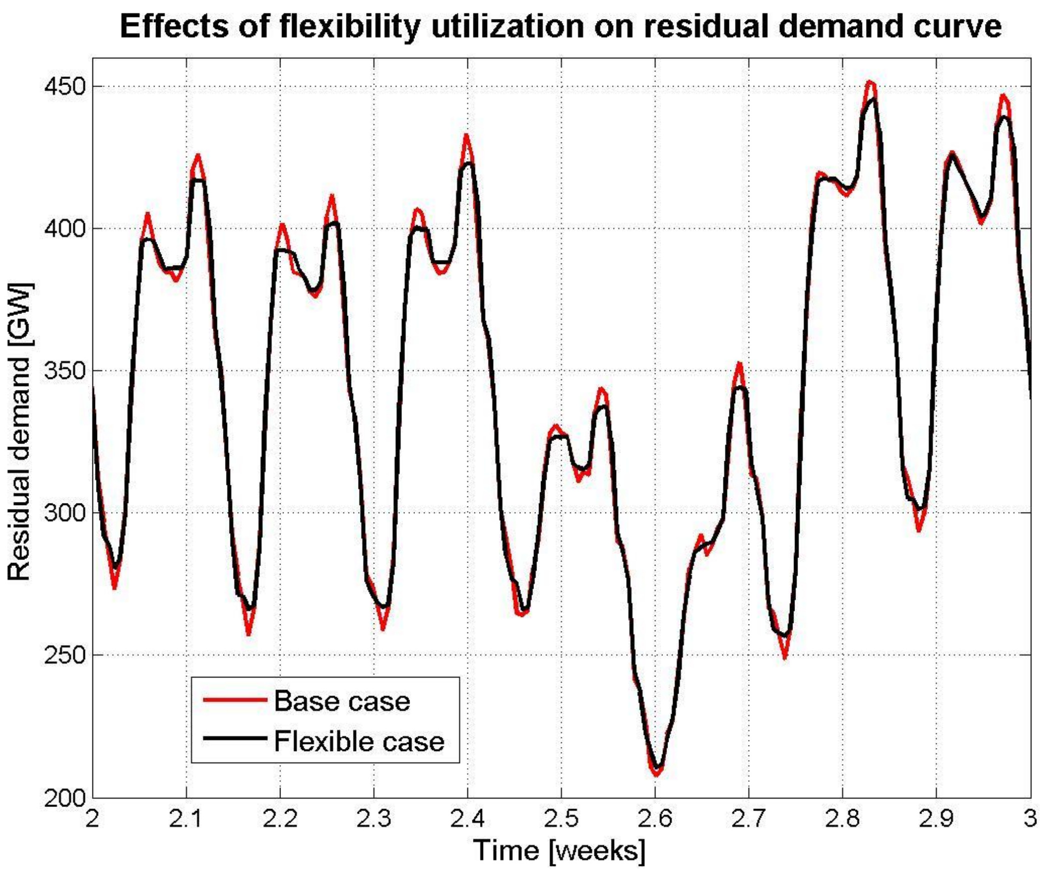

Figure 2 Effects of utilization of flexibility on the residual demand curve on a winter week in the EU-28 area for 2030. In red, the base scheduled demand is shown, without utilization of flexibility, and in black the optimized demand with the utilization of flexibility from smart appliances. The week shown in figure starts with Wednesday 00.00 am and ends with Tuesday 11.00pm.

According to the expectations, the figure shows that the flexibility from smart appliances is used to flatten the peaks in the residual demand curve caused by the intermittent RES production and the base case demand curve. The flexibility is utilized optimally, but within own specified constraints, such as for instance, limited shifting time. Therefore, there are still some peaks remaining in the residual curve from the flexible case.

In the figure, on the fifth day of the second week, just after mark for 2.6 weeks on the horizontal axis in the figure, there were two small sharp peaks in the base case residual curve (red line). They were compensated for by the flexible demand shifting in the flexible case, as can be seen in the black line. By smoothing the residual curve in this way, the system experienced benefits. For instance, the ramp up and ramp down costs of the conventional dispatchable units were decreased, which had a positive effect on the total costs.

In general, it can be observed that the flexibility is used in particular to reduce the peaks in the residual demand curve. These peaks take place during the peak others (maximal peak value), which in winter take place around noon, and in the late afternoon hours, and during the low residual demand time, which typically take place in the night, between 2 and 5 am. Secondly, it can be seen that the flexibility is utilized to smoothen the residual demand curve, as explained above. The smoother the residual curve is, the more of cheaper baseload technologies can be scheduled. This impacts all the chosen KPIs in a positive way.

In Figure 3, a stack diagram of the demand side flexibility from smart appliances is shown against the fixed, nonflexible part of the demand. It is shown for a summer week in Germany in 2030 scenario, in which there was the largest number of the enabled smart appliances compared to all the other benchmark years. The demand is shown for Germany; however, similar trends and ratios can be observed in all the member states, and therefore also in the aggregated EU-28 area. Green stack in the figure represents the flexibility from periodic appliances and energy storage appliances, which are modelled purely as demand shifting. Dark red stack represents the flexibility from HVAC appliances, which are modelled as complex demand shifting. Finally, the nonflexible, fixed part of the demand is shown in blue stack. Flexibility from residential energy storage is not shown in the figure, as it is modelled as storage and not demand shifting, and as such, it has no defined base demand. Nevertheless, this flexibility is utilized in the use case for the same purposes as the demand shifting flexibility.

Although at every time instance, there is some flexibility from smart appliances, and also from both, periodic appliances and energy storage appliances, and from HVAC group of appliances, the shares of flexible demand compared to the total demand are quite low, as also summarized in Table 5. In fact, yearly average share of flexible smart appliances demand in the total demand in EU-28 is as low as 3.391% in 2030, 0.847% in 2020, and 0.134% in 2014. These shares are expressed as the total energy of flexible demand in a year over the total demand energy in the same year. The peak power of flexible demand is a relevant indicator of the amount of demand side flexibility. The peak power of flexible demand from smart appliances is computed to be 2,767MW, 10,621MW, and 37,732MW for 2014, 2020, and 2030, respectively. Expressed as percentage of the total demand, these numbers result in 0.896% for 2014, 3.364% for 2020, and 10.323% for 2030.

Table 5 Share of flexible demand over the benchmark years

Year	Share of flexible demand energy in the total demand energy	Share of peak flexible demand in the total demand	Peak flexible power in the EU-28 area [MW]
2014	0,134%	0,896%	2,767
2020	0,847%	3,364%	10,621
2030	3,391%	10,323%	37,732

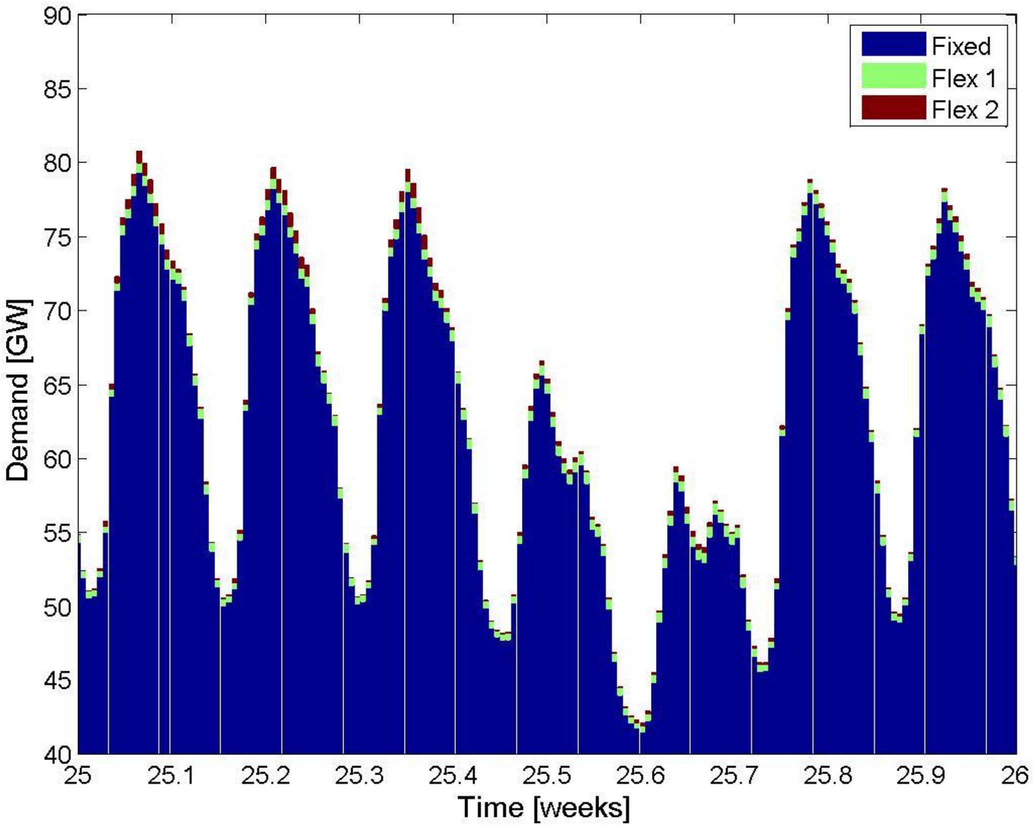

Figure 3 Demand side flexibility from smart appliances (green from periodic appliances and energy storage appliances, and red from HVAC appliances) against the fixed demand (blue) in Germany on a summer week in 2030.

Figure 4 is an equivalent of Figure 3, but instead of a summer week as in Figure 3, a winter week is chosen in Figure 4. The colour legend remained the same, as well as the member state (Germany) and benchmark year for which the data is shown. It is interesting to observe a shift in flexibility potential in the two groups of flexibility: whereas in winter, more flexibility from HVAC appliances is available, in the summer months, there is more flexibility available from the energy storage and periodic appliances. Moreover, it is clearly visible that the demand in winter months is higher than in the summer months, and that also there is more of flexible demand in winter months than in summer months.

Both figures, Figure 3 and Figure 4, clearly show how much more demand is nonflexible than flexible. Nevertheless, even with such an amount of unlocked flexibility from demand side[9], benefits to the system can be observed, as will be discussed next in more detail.

[9] Flexibility from demand side is not necessarily only flexibility from smart appliances.

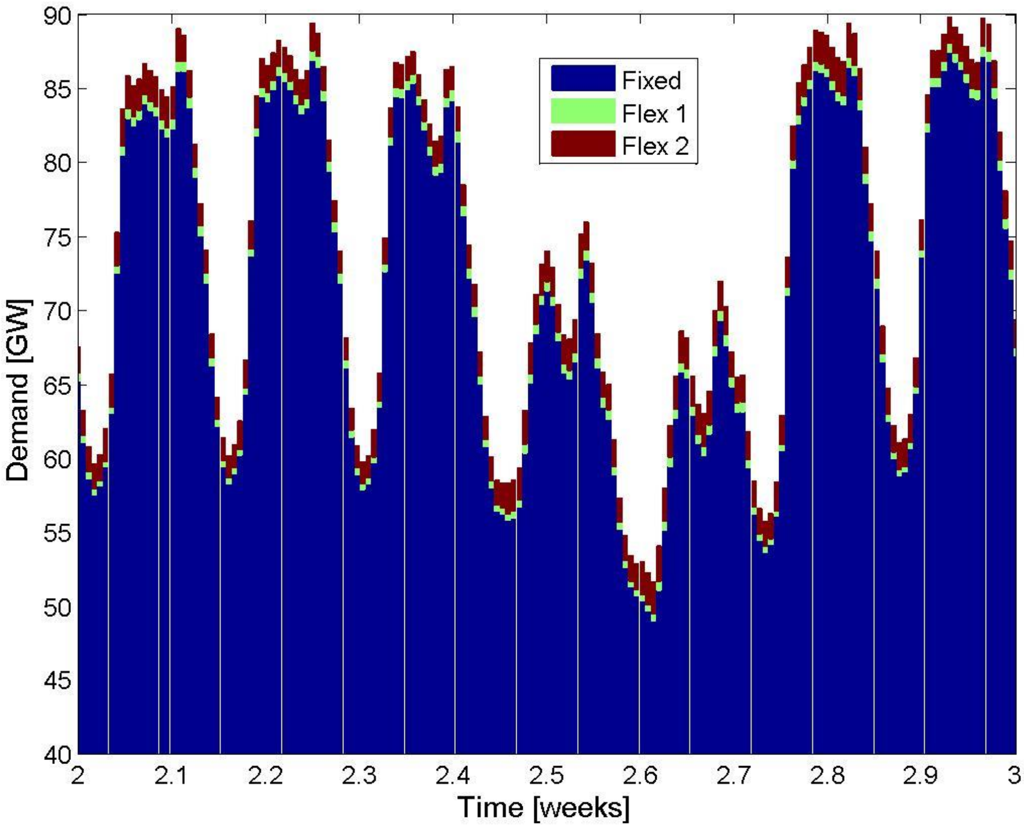

Figure 4 Demand side flexibility from smart appliances (green from periodic appliances and energy storage appliances, and red from HVAC appliances) against the fixed demand (blue) in Germany on a winter week in 2030.

→ **Calculated benefits from the smart appliances**

To put a value on the flexibility of smart appliances, let the indicator ΔKPI be the difference in the KPIs computed in the base case, and the KPIs computed in the flexible case. Previously, the three KPIs, namely the total costs, total CO_2 emissions and the efficiency of the utilized generation mix, which is related to the primary energy savings, were determined for the base case in Task 5, where no flexibility of the smart appliances is used. These indicators are denoted by $KPI1_{ref}$, $KPI2_{ref}$, and $KPI3_{ref}$. Here in Task 6, the same indicators are computed for the case with the modelled smart appliances flexibility, as presented in Table 4 KPIs for the day-ahead use case for each of the benchmark years and Imbalances between production and consumption of energy should be mitigated in real-time. Figure 5 illustrates graphically the 3 main origins of imbalances and their forecasted evolution in 2020 and 2030. The 3 sources of imbalance are deviations in the expected production of wind and solar and deviations in the forecasted consumption. In general, deviations in consumption will remain the most important cause of imbalance and are expected to increase by 2030 due to the average increase in consumption. However, although the share of wind and solar in the total imbalance across the year, might be relative small (but increasing), it does not mean they do not put the system under pressure. On the contrary, the deviations in wind and solar might be very big at particular moments, and if they happen in combination with for example low consumption (holiday, weekend, night), there is a need for fast responding and flexible devices that could react to guarantee security and stability of the electricity system. Smart appliances can play a role during these specific events.

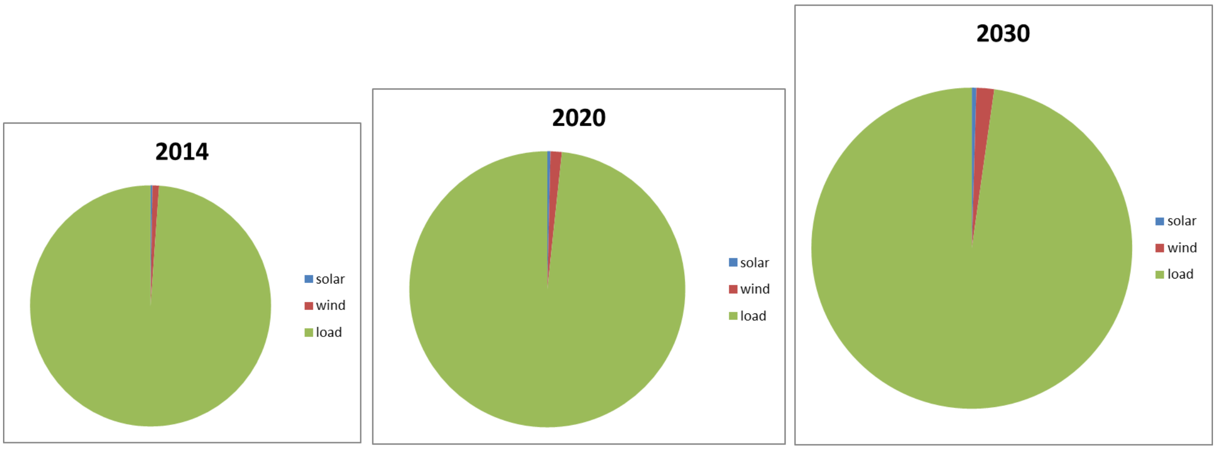

Figure 5 Imbalances by cause in the three benchmark years for the overall EU-28 area.

Table 11 gives the overview of the imbalance use case for 2014, 2020 and 2030. On average, the cost for imbalance (KPI1) increases between 2014 and 2030, mostly due to the increase of forecast errors (by load, wind and solar), and also due to the increase in fossil fuel and CO_2 emission prices. For KPI2, the CO_2 emissions decrease to almost zero in 2030. This is due to the fact that basically all imbalances are solved by the use of smart appliances (instead of conventional generation), which have a zero emission. Also the efficiency of the utilized generation mix increases due to the higher share of smart appliances.

Table 11. These indicators are denoted by $KPI1_{flex}$, $KPI2_{flex}$, and $KPI3_{flex}$.

Finally, on basis of these numbers, ΔKPIs (the savings in total costs, savings in CO_2 emissions, and increase in utilized generation mix efficiency) are computed as the difference between the two. More precisely, the savings in total costs and CO_2 emissions are computed as the difference in obtained KPIs with and without flexibility from the smart appliances:

$$\Delta KPI1 = KPI1_{ref} - KPI1_{flex}, \qquad \Delta KPI2 = KPI2_{ref} - KPI2_{flex}, \qquad \Delta KPI3 = KPI3_{flex} - KPI3_{ref}.$$

Note that the sign in ΔKPI3 is different from the one defined in ΔKPI1 and ΔKPI2. This is chosen so that ΔKPIs are always positive if smart appliances are contributing to better economical and/or environmental system performance.

In Table 6 Differences in KPIs as a consequence of utilization of flexibility from smart appliances for the day-ahead use case and each of the benchmark years, differences in KPIs, ΔKPIs, as a consequence of utilization of flexibility from smart appliances for the day-ahead use case and each of the benchmark years are presented.
The general trend that can be observed in the results is that the more flexibility there is, the better economic and environmental indicators become, which was to be expected. Note that ΔKPI2 is given in kt of CO_2 emissions, whereas KPI2 was expressed in Mt of CO_2 emissions.

Table 6 Differences in KPIs as a consequence of utilization of flexibility from smart appliances for the day-ahead use case and each of the benchmark years

Day ahead use case	ΔKPI1 (savings in total system costs) [M€]	ΔKPI2 (savings in CO_2 emissions) [kt]	ΔKPI3 (primary energy savings) [%]
2014	8,8	60	0,01
2020	54,5	770	0,05
2030	1710,5	3880	0,29

The increase in the efficiency of the utilized generation mix, ΔKPI3, changes the least with the addition of flexibility of smart appliances.

To put the savings in total system costs further in perspective, Table 7 gives the savings as percentage of the total system costs for electricity production, and compares it to the share of flexible demand in the total demand (in terms of energy and not peak power). Over the years, not only the absolute value of savings increases, but also the savings computed as percentage of the total system costs tend to increase, with the largest amounts for 2030 scenario, when there is the most flexibility, and when also the fuel and CO_2 emission prices are highest.

Table 7 Savings in total costs due to utilization of flexibility from smart appliances, and share of flexible demand in the total system demand

	Savings as % of the total costs	Share of flexible demand in the total demand (energy-wise)
2014	0,01%	0,134%
2020	0,07%	0,847%
2030	1,48%	3,391%

In table 8, an overview is given from the evolution of the average value of the hourly marginal electricity prices with and without the use of flexibility. In general, electricity prices are expected to increase significantly by 2030, primarily driven by the increase in CO_2 costs (see assumptions on fuel costs in task 5). Nevertheless, the table below shows that the use of flexibility from smart appliances in 2030 could lead to an average decrease of marginal electricity prices of almost 5% (without considering the cost to use this flexibility), which is a significant decrease in the electricity price, in particular taking into account that the peak share of flexible demand was maximally 10,3 % (see also Table 5), and energy share of flexible demand was on average 3,4%.

Table 8 Marginal electricity prices for the day-ahead use case, base and flexible case: differences due to utilization of flexibility from smart appliances

year	flexible case [€/MWh]	base case
2014	42,62	42,70
2020	52,91	52,94

2030	92,97	97,03

The KPIs as presented above are defined on the system level, and as such, they quantify the operation of the system as a whole using the flexibility of all the smart appliances together. Therefore, KPIs cannot straightforwardly, without introducing additional assumptions, be determined separately per smart appliances category or even per smart appliance. In other words, there is no simple way to completely accurately distinct in resulting benefits from flexibility among smart appliance groups. Nevertheless, on basis of this schedule and additional information from tasks 1-3, and the optimal schedule of different flexibility groups (group 0 – group 3), an approximation of the value of benefits per enabled smart appliance per year from the computed total system benefits is extracted as described below.

In order to calculate the value per appliance for 2014, 2020 and 2030, 3 steps are taken:

Firstly, the total benefits (ΔKPI1), are distributed across all the flexibility groups on the basis of the optimal shifted flexible demand profile. This is done by multiplying the hourly marginal realized prices from the reference case with the difference in baseload flexibility profile (= the available amount of flexibility during each hour before any shifting) and optimal shifted flexibility profile. This means that if flexibility from a certain group of smart appliances is mainly used during 'expensive hours', the allocated value will be higher. These values are presented in table 9.

Second, for each group of flexibility (0-3), the value is allocated to individual appliance groups based on the average energy consumption of each group, i.e. the higher the average energy consumption, the higher the allocated value (due to the higher shifting potential).

Third, in order to calculate the value for each individual appliance, the benefits per appliance group are divided by the number of smart enabled appliances (see task 2). The overview of the value per individual appliance is given in table 10.

Table 9 Value of flexibility per different flexibility group, expressed as earnings per shiftable energy capacity €/MWh. Group 1 represents the flexibility that can be shifted for 3h (dishwashers, washing machines, tumble dryers), group 2 the flexibility that can be shifted for 1h or less (flexibility from energy storing appliances and commercial refrigeration), and group 3 stand for residential and tertiary cooling and heating, which can be shifted for 1 hour, however there is an additional constraint to avoid loss of comfort.

year	Group 0 (storage) [€/MWh]	Group 1 (3h) [€/MWh]	Group 2 (1h) [€/MWh]	Group 3 (1h extra) [€/MWh]
2014	3,40	0	0	1,96
2020	3,76	6,04	3,23	1,59
2030	34,51	34,14	13,31	13,88

Table 10 Value of benefits due to flexibility of smart appliances per enabled smart appliance per year (given in [€/year/appliance]).

Value of benefits per enabled smart appliance per year		2014	2020	2030
Periodical appliances	Dishwashers	0€	17,18€	7,53€
	Washing machines	0€	1,15€	6,39€
	Tumble dryers	0€	4,03€	10,52€
Energy storing appliances	Refrigerators and freezers (residential)	0€	0,23€	1,11€
	Electric storage water heaters	0€	1,18€	6,37€
Residential heating and cooling	HVAC residential cooling (heat pump)	0,79€	0,92€	11,24€
	HVAC residential heat pump heating	1,02€	1,19€	14,50€
	HVAC residential Joule heating[10]	0€	1,88-15,02€	9,64 – 75,62€
Tertiary heating and cooling	HVAC tertiary cooling	14,65€	17,04€	208,11€
	HVAC tertiary heat pump heating	6,24€	7,26€	88,71€
	HVAC tertiary Joule heating	0€	1,81-14,44€	9,65 – 77,09€
Commercial refrigeration	Tertiary cooling (heat pump) [11]	0€	1,45€	29,20€
Residential energy storage systems	Home batteries[12]	212,63	235,6	2160,38

[10] The value is depending on the technology, and there is no difference for residential and commercial buildings due to lack of data. For 2020 scenario, the following values are found: for electric radiator without inertia 1,81€/appliance/year, for electric radiator with inertia 3,01€/appliance/year, and for boilers 15,02€/appliance/year. For 2030, the following values are found: for electric radiator without inertia 9,65€/appliance/year, for electric radiator with inertia 15,44€/appliance/year, and for boilers 77,09€/appliance/year

[11] Per evaporator.

[12] From Table 3, it can be computed that the average installed energy capacity of each home battery is approximately 7 kWh.

6.3.3. IMBALANCE USE CASE

Imbalances between production and consumption of energy should be mitigated in real-time. Figure 5 illustrates graphically the 3 main origins of imbalances and their forecasted evolution in 2020 and 2030. The 3 sources of imbalance are deviations in the expected production of wind and solar and deviations in the forecasted consumption. In general, deviations in consumption will remain the most important cause of imbalance and are expected to increase by 2030 due to the average increase in consumption. However, although the share of wind and solar in the total imbalance across the year, might be relative small (but increasing), it does not mean they do not put the system under pressure. On the contrary, the deviations in wind and solar might be very big at particular moments, and if they happen in combination with for example low consumption (holiday, weekend, night), there is a need for fast responding and flexible devices that could react to guarantee security and stability of the electricity system. Smart appliances can play a role during these specific events.

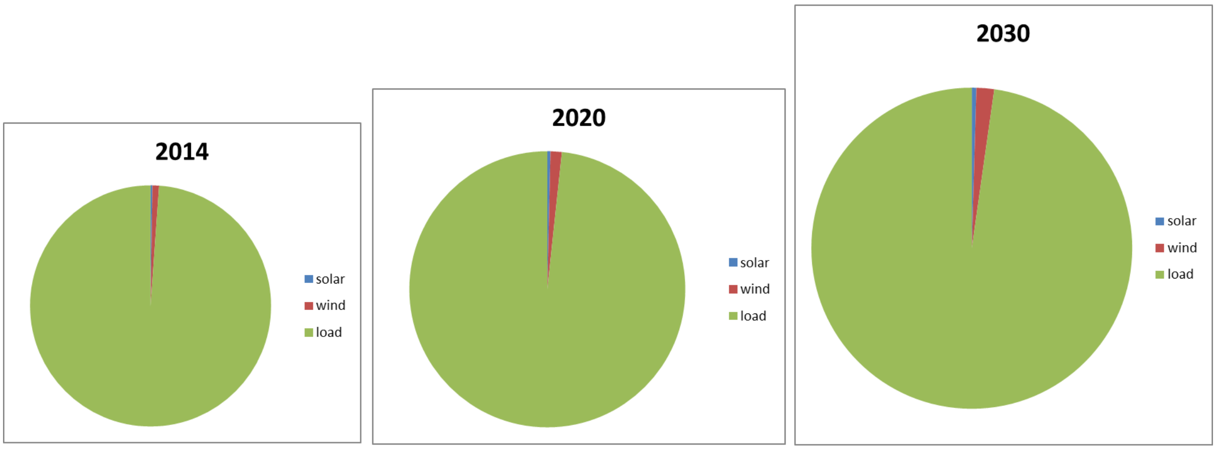

Figure 5 Imbalances by cause in the three benchmark years for the overall EU-28 area.

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Table 11 KPIs for the imbalance-ahead use case for each of the benchmark years

Imbalance use case	KPI1 (total system costs) [M€]	KPI2 (CO_2 emissions) [Mt]	KPI3 (efficiency of the utilized generation mix) [%]
2014	5,64	1,55	54,36
2020	9,77	1,04	58,14
2030	12,17	0[13]	61,34

[13] This indicated that all the imbalance volumes are balanced by the flexibility from smart appliances.

In table 12, the difference of comparing the calculated KPIs with the benchmark values (as presented in task 5), show that there is an important decrease in system costs, most noticeable in 2030, due to the use of smart appliances. Also with respect to CO_2 emissions, a large decrease can be observed, due to the zero emission factor applied for smart appliances. Overall, it is clear that, mainly in 2030, due to increasing CO_2 costs and fuel prices, the benefits coming from smart appliances are high.

Table 12 Differences on KPIs as a consequence of utilization of flexibility from smart appliances for the imbalance use case and each of the benchmark years

Day ahead use case	ΔKPI1 (savings in total system costs) [M€]	ΔKPI2 (savings in CO_2 emissions) [kt]	ΔKPI3 (increased in efficiency of the utilized generation mix) [%]
2014	1,57	10	0
2020	1,43	610	0,03
2030	131,49	1780	0,29

The individual values per appliance for the imbalance use case are not detailed here but are in the same order of magnitude as for the day-ahead use case. This statement is further supported by the fact that the values awarded today for flexibility in the reserve market (R3DP) in Belgium (= imbalance use case) are in the same order as the values reported in table 9 of this report (day ahead use case). For 2016, a value of 3,14€/MWh was awarded for flexibility, coming from the distribution grid[14].

6.3.4. OTHER USE CASES

Within the scope of this preparatory study, the benefits of the flexibility from smart appliances are evaluated for the day-ahead case and imbalance use-case, as presented above. Nevertheless, these are not the only possible use cases for the flexibility from smart appliances, as discussed earlier in Task 2.

There are additional interesting use cases, namely:

- the grid congestion use case, and
- reactive power voltage support use case

The grid congestion use case is possibly relevant on all grid voltage levels: in the high voltage (TSO) network, and in the low and middle voltage (DSO) network. Today, it is not possible to build a sound evaluation of benefits from smart appliances flexibility due to a lack of data. The business cases where smart appliances are used to offer services to grid operators to solve congestion are less mature due to several regulatory barriers (e.g. DSOs not remunerated for flexibility contracted to solve congestion). Nevertheless, these use cases could form a good business opportunity for smart appliances flexibility, and possibly additional benefits could be gained there.

[14] http://www.elia.be/en/suppliers/purchasing-categories/energy-purchases/Ancillary-Services-Volumes-Prices

6.4. EVALUATION OF COSTS AND BENEFITS

6.4.1. EVALUATION OF COSTS AND BENEFITS FOR THE ENERGY SYSTEM

Smart appliances can provide energy system services both in day ahead and in real-time by shifting operation and as a result, adapting the consumption. In day ahead, this leads to a reduced cost and CO2 emission compared to a situation without smart appliances, due to the fact that additional generation by conventional power plants could be avoided due to a smart shift in load. In real-time, the same benefit of smart appliances can be observed in case a shift in demand by smart appliances avoids additional production by conventional generation units. In addition, the use of smart appliances also leads to a reduction in curtailment of RES in case there is too much intermittent energy production compared to the demand.

In conclusion, the use of flexibility from smart appliances is not necessarily reducing the electricity consumption in total. However it reduces the need for more expensive and more polluting conventional generation units at moments of peak load or large imbalance. This leads to both monetary savings for the system and reduced CO2 emissions, which in the framework of the ETS not only has an environmental but also an economic value.

The quantification of these system benefits is detailed in previous sections of this document. Please note that the benefits are determined for flexibility at the level of a specific flexibility category (groups 0 -3 as defined above). In the optimisation, the assumption is made that the marginal price of flexibility is zero, to allow a maximal use of flexibility. This means that the analysis is a representation of the maximum potential that flexibility might have in the current and future energy system.

In a second step, in order to determine the viability of the business cases of the use of flexibility of smart appliances, one should also analyse the cost side to enable this flexibility to participate in the market. It is obvious that the flexibility of smart appliances will only be used in a real market situation if these costs are lower compared to the benefits. The quantified benefits can therefore be seen as an upper bound.

The benefits calculated are the total benefits for the system which means that the benefits will need to be compared with the total costs of the entire value chain of smart appliances, from producer until the end-user. As the benefits of the flexibility are supposed to be passed on to the end consumer, the other partners in the value chain will require a share of the value of flexibility via the price they will charge to the end consumer for the production of the smart appliance or the delivery of certain services enabling the flexibility of smart appliances to participate in the market. It will depend on elements such as market power, subsidy systems, sector rules, EU and Member State regulations, how the system value of flexibility will be divided across the value chain and, as a result, what will be the final benefit awarded to the end consumer, compared to a situation where the end consumer is not investing in a smart appliance.

The costs and benefits for the energy system can be summarized as follows.

- The flexibility provided by smart appliances can support the energy system in many ways:
    - It can optimize the planning in day-ahead (day-ahead use case) by replacing expensive gas and coal units during moments of peak consumption. This optimization results in a decrease in costs for the system and a reduction in CO_2 emissions.

  - It can support the system in real-time (imbalance use case) in case production is not sufficient to cover the demand. Similar to the day-ahead use case, flexibility from smart appliances can be used to avoid the activation of gas or coal power plants by energy producers or network operators on the one hand or the possibility of load shedding on the other hand. This results again in a decrease in costs for the system and a reduction in CO2

  - It can support the system in real-time in case there is too much production which could not be stopped in an economic efficient way (e.g. in a situation where high amount of wind and solar energy are produced) or alternatively, in case demand is much lower compared to the initial forecast. The use of flexibility from smart appliances can in this case prevent the curtailment of wind and solar energy in the system. As a result, the use of smart appliances allows an increase in hosting capacity of renewable energy.

- Another important element is the fact that home battery systems, in combination with solar panels are not only supporting the system, but are also increasing the share of self-consumption. This has additional benefits, such as a potential reduction in grid tariffs as there is less need to increase the capacity of the distribution grid,…

- The benefits the flexibility of smart appliances have a clear value for the energy system. This value has to be compared with the cost or minimum remuneration owners of smart appliances require offering their flexibility to the market. The cost differs dependent on the characteristics of the flexibility (shifting potential, average shifting period) but also on the cost of the smart appliance (purchase, maintenance, and reduced life-time of the smart appliance if used in a more flexible way). In addition, possible loss of comfort could also require an additional compensation on behalf of the owners of flexibility.

- Within the scope of this preparatory study, the benefits of the flexibility from smart appliances are evaluated for the day-ahead case and imbalance use-case. There are additional use cases, such as support for grid congestion (on the TSO and DSO grid) that are not detailed in this study due to a lack of existing data. Today, these use cases are indeed rather immature due to e.g. existing regulator barriers. Nevertheless, they are expected to become more promising in the coming years.

6.4.2. EVALUATION OF THE COSTS AND BENEFITS FOR THE END-USER

→ Financial benefits for the end-user

As indicated in

Table 10, the added value of the DSF per end-consumer appliance, when committed in the day ahead electricity markets, is estimated to be up to 18€/year in 2020 and up to 77€/year in 2030, with ranges varying strongly between appliances. When committed in the imbalance markets, the added value is the same order of magnitude. Note that for the valorisation of this added value, investment and operational costs should be covered of both the end consumer and other actors such as the aggregator or ESCO.

As stipulated in section 6.3.4, DSF can also be used for other applications, such as grid congestion management or other ancillary reserves, the value of which may be higher than these figures. The added value for these cases is country, region or even district dependent. E.g., in districts in which all houses are equipped with photovoltaic panels and heat pumps, the value of DSF for grid congestion management will be significantly larger than the value for day ahead or imbalance markets. An example of where such situations are emerging is the 'Stroomversnelling' project[15] in the Netherlands, which has the ambition to mass-renovate entire districts totalling 111.000 renovates buildings by the end of 2020 and where the mass installed photovoltaic panels and heatpumps have already necessitated local grid re-enforcements.

→ **Additional investment and operational costs**

Cost elements that need to be considered from an end consumer perspective are the initial investment costs on the one hand and the recurrent operational costs on the other hand which can be specifically attributed to the DSF functionality of the appliance.

The operational cost consists of the operating cost of the communication infrastructure and the costs related to increases in energy consumption. The latter is discussed separately below. The in-house communication infrastructure is mostly shared with other devices and applications. The operational cost that can be attributed to the smart appliances is therefore case dependent, but is assumed to be very low or negligible compared to the investment costs.

Analysis of publicly available information and contacts with industry have made it clear that it is very difficult to derive generalised estimations of the additional investment costs that can only be attributed to the DSF feature specifically subject to this Lot 33 Preparatory Study. Below, a summary is given of the findings elaborated in Task 4.

When looking at the market, it seems that some premium segment household appliances (periodical, continuous and behavioural) currently available on the market are already network connected and dispose of sufficient computational power as a basic requirement to allow DSF. These appliances include washing machines, tumble dryers, dishwashers, cooling appliances, hobs and ovens, range hoods and water heaters. For these appliances, additional costs to allow DSF mainly relate to software development, testing and documentation. In case the appliance is not yet network connected, features also need to be added in the form of additional computational power, a printed circuit board, wires and a wireless connectivity module.
Additional costs of the necessary adaptations specifically attributed to the DSF feature will mainly depend on the amount of products in the series of appliances produced. Assuming larger product series in a context of a future smart grid market, cost levels at manufacturer's level including testing and documentation are estimated as follows:

- A networked appliance only needing software modifications, testing, documentation etc.: 5-10€
- A non-networked appliance also needing a network connectivity module etc.: 15-20€

These additional manufacturing costs make abstraction of R&D costs and are exclusive of mark ups for distribution and retail level.

The Task 4 report has also identified the technical adaptations required to enable DSF including the involved costs for the HVAC appliance category which represents an important share of the total consumed energy in the EU. Heating and cooling appliances involved are the following: electric radiators, thermal storage radiators, electric boilers and circulators, heat pumps and air conditioners.

[15] http://www.stroomversnelling.net

The necessary modifications and involved costs can be divided according to the so-called *joule effect appliances* (radiators, thermal storage radiators and boilers and circulators) on the one hand and the *thermodynamic appliances* (heat pumps and air conditioning) on the other hand.

For the joule effect appliances, the link between the aggregator and the appliance can be made either with an electronic thermostat capable of receiving and exchanging signals with the grid (in this case only software adaptability is required) or via an adaptor (requiring hardware and software modifications). As assessed in Task 4, the following costs are estimated for the changes of the joule effect appliances:

- A networked joule effect only needing software modifications (with an electronic thermostat i.e.), testing, documentation etc.: 5-10€
- A non-networked appliance also needing a network connectivity module etc.: 10-15€

In the context of this study, thermodynamic appliances involve a vapor compression cycle with the input of energy (in this case electricity) being consumed by the compressor in order to exchange heat between outdoors and indoors. Input from industry indicated that adding DR to a heating device using a vapor-compression cycle would raise the retail price approximately with 100€-200€ including software adaptation and development, installation costs, intervention etc. According to the authors of this Task report, this should rather be considered as the high end of the range of additional costs. These costs are assessed to include research & development costs and costs associated with the first appliances being produced in small series in a short term perspective, knowing that purchases prices of adaptors and electronic thermostat are in the range of respectively 10€ and 2€ per piece.

Apart from the benefits related to the use of flexibility from an energy system perspective, other benefits and costs are relevant from an end-user perspective, these are addressed in the following sections.

→ **Positive/negative impact on the energy consumption**

The use of the DR flexibility may result in operating points that deviate from the most energy efficient operation point, e.g., by cooling deeper or heating higher. However, the assumptions underlying the estimates of the value of flexibility in this study were chosen in such a way that this surplus consumption is considered to be negligible.

Therefore it should be clear that more flexibility would potentially be available if less efficient operating point are permitted. In this case, the end-user should be compensated for this surplus energy consumption with an acceptable margin that still lies within the surplus added value of providing the extra flexibility. From a system perspective, this can be interesting provided that such a case allows for increased share of RES, leading to reduced CO_2 emissions despite the surplus energy consumption.

If the appliance is equipped with extra DSF specific electronics, then the operation of these may cause a small to negligible surplus electricity consumption, as discussed in Task 4. On the other hand, the functionality required for DSF support also offers opportunities for improved energy efficiency, as smart appliances allow a detailed view of the energy consumption of those appliances. A number of studies [Darby 2006; Fischer 2008; Ehrhardt-Martinez 2010; Faruqui 2010; Stromback 2011: Lewis 2014] have assessed the effectiveness of energy use feedback (broadly defined, taking into account multiple feedback channels ranging from awareness campaigns to dedicated in-home displays showing energy consumption in real time), mostly in terms of achieving energy savings. These studies show consistently that there is considerable case-to-case variation of reported energy savings, typically in the range of 0 - 20%[1], with usual savings between some 5 and 12% [Fischer 2008]. Variation may be explained by a variety of factors other than the feedback design, including the climate conditions, the length of pilot, the number of participants and the level of education provided [see Stromback 2011 for an overview]. Studies specifically addressing smart meters have demonstrated that providing detailed electricity consumption information to end consumers, in the combination with advice on how to reduce energy consumption result in significant electricity consumption savings of up to 8% per household[16].

Secondly, the measurement and control functionality, required for DSF functionality, can also be used to analyse and optimize the operation of the smart appliance from an energy efficiency point of view[17]. Smart appliances also allow a more user-friendly operation (e.g. through use of apps as opposed to manuals) which leads the end-user to the optimal operational setting under the given circumstances. Even though quantitative evidence is not yet available, the operational mode which is advised by the smart setting is expected to be more energy efficient compared to the setting the end-user would choose manually. The degree of increased energy efficiency will depend on various factors such as the specific smart appliance (e.g. more potential for a dishwasher compared to a washing machine), risk aversion from the end-user (e.g. washing at higher temperature which may be more optimal), potential rebound effects (e.g. end-user is more confident to use the appliances), etc.

→ **Impact on comfort**

Generally, one of the key arguments convincing consumers towards home automation and communication-enabled appliances is the increased comfort and ease of use. The functionality and infrastructure required for the support of DSF, and shared with IoT applications in general, also offers opportunities in this area. Examples are improved user interfaces, possibly through apps, as for instance demonstrated in the Smart Domo Grid project[18], preventive maintenance, etc.

As discussed in detail in Task 3, the additional impact of supporting demand response flexibility is strongly device dependent. The results of the analysis done in Task 3 regarding the impact on the comfort of the end-consumer is summarised below for each appliance type.

For periodical appliances like washing machines, dishwashers, tumble dryers and washer-dryers consumers may feel uncomfortable operating their appliances unattended because of safety aspects (e.g. fear of flooding or fire). These concerns could be addressed by improving safety features of the appliances and by offering relevant insurances. Quite a few appliances available on the market are already equipped with safety features like aqua stop valves, which protect water damages by cutting off water supply immediately in case of emergency. The end-consumer's comfort may also be compromised by noise during operation of appliances at night. Innovative technologies like frictionless magnetic motors or low-vibration components, which are already offered on the market, may help to overcome this problem in future. In view of washing machines, tumble dryers and

[1] Reported ranges: 0-15% [Darby 2006], 1-20% [Fischer 2008], 4-12% [Ehrhardt-Martinez 2010], 3-13% [Faruqui 2010], 2-12% [Stromback 2011].

[16] Eandis, Infrax, "*POC II Smart Metering, energie-efficiëntie, resultaat verbruik*"

[17] See, e.g., the 'smart control' functionality as defined in the Ecodesign requirements for water heaters and hot water storage tanks, set via regulation No 814/2013 of 2 August 2013: 'smart control' means a device that automatically adapts the water heating process to individual usage conditions with the aim of reducing energy consumption.

[18] http://ses.jrc.ec.europa.eu/smart-domo-grid

washer-dryers, potential further impacts on comfort are related to textile damages including fading of colours, mould and wrinkles if the drying process is not started immediately after the washing process is finished. Such textile damages can be avoided by means of comfort settings e.g. defining a maximum length of power interruptions or prompting the drum to tumble in certain intervals after the washing process is finished.

In the case of cooling appliances like refrigerators and freezers (residential and commercial), there is no impact on consumer's comfort as far as food quality and safety is not compromised and the appliance works reliably. These appliances operate fully automatic and therefore consumers will hardly notice smart operation. The possibility to monitor storage temperatures might easily help to overcome concerns in view of food safety and quality.

In view of electric storage water heaters, a lack of hot water may compromise consumer's comfort, especially in case of appliances with low storage capacities. As far as devices with large storage capacities are concerned or comfort settings are induced (e.g. defining a minimum state of charge), comfort losses are small or non-existent.

For all behavioural appliances, DSF would have significant impacts on consumer's comfort, as their operation requires an active involvement of the consumer and the latter wants the service being available directly upon request.

In case of HVAC appliances, impacts on consumer's comfort are related to temperatures exceeding a comfortable range. This range is defined in the EN 15251 standard, with the inside temperature not falling below 18 °C (19 °C for tertiary buildings) in winter and not exceeding 27 °C in summer, with a maximum variation of 2 °C/h. The same standard gives guidance regarding standard air flow rates by person and admissible pollutant concentration in buildings. As far as these permissible values are not exceeded, impacts on comfort are assumed to be low.

Regarding battery chargers, consumer's comfort may be significantly compromised if the state of charge is not sufficient on next usage. Reliable predictions are necessary to overcome these concerns.

In case of energy storage systems, there is no negative impact on consumer's comfort. In contrast, as a benefit they may provide backup power when the grid is not available.

The negative comfort impact by DSF enabled lighting is naturally a serious constraint as light is used when there is a need. Comfort impacts also include safety issues for both, residential and commercial areas. For street lighting, the comfort impacts may not be that significant, especially if they are limited in time.

→ **Risk of unequal distribution of costs and benefits**

The extra functionality of smart appliances implies a surplus cost. The distribution and size of this surplus cost depends strongly on the choice for a mandatory or non-mandatory approach. In case of a mandatory approach, the extra cost per appliance is the lowest due to the scale advantage. However, mandatory measures also imply that the costs are socialized and distributed across all appliance owners, including those owners that do not use and receive added value from the demand response flexibility. The latter is avoided with a non-mandatory approach. However, in this case the surplus cost of a smart appliance will be higher due to the loss of the scale advantage. There is then also the risk that smart appliance ownership for less fortunate people is hindered, and that they share less in the added value of demand response.

Most smart appliances, as envisioned today, depend on internet access. This threatens to exclude those people without internet access from sharing in the added value of smart appliances. One method to circumvent this, is to stimulate LPWAN support by smart appliances. Another is to support the use of the smart meter as a communication link.

The distribution of costs and benefits depends strongly on the energy market organisation. If consumers in a certain region or country have no or less access to DR programs, then they can also share less in the added value. A consumer right for access to variable tariffs or other DR mechanisms can alleviate this, as are actions to organize the energy market so that DR is supported or other governmental support schemes for demand response.

→ **Risk of vendor lock-in**

Unlocking demand side flexibility requires smart appliances to cooperate with components outside of the appliance, e.g., an energy gateway, cloud systems, etc. This creates risks for vendor lock-ins, both to the vendor or manufacturer of the appliances, and to the energy retailers. It must be possible to use and interchange any smart appliance of any brand/vendor in any demand response program. The use and support of open standards is essential to achieve this. Also the energy market design has an impact on this matter, more specifically in the links between demand response programs and/or aggregators on the one hand and the energy retailers on the other.

6.4.3. EVALUATION OF THE COSTS AND BENEFITS FOR INDUSTRY

Based on the limited available data on additional costs (see Task 4 and previous section), it has not been possible to make an analysis of the impacts on industry regarding required investment levels and the derived impacts on the sectors' profitability, competitiveness and employment. The market trends/forecasts described in Task 2 clearly showed that digital communication functionality will be a common (commodity) function in most appliances sold from 2020 onwards. Manufacturers will most likely include digital communication functionality in all or (at least) in special product series for all product categories in the scope of this Preparatory Study, leading to 'connected' (communication-enabled) and 'app-enabled'[19] appliances.

However, this tendency does not imply that these appliances will be interoperable or will provide DSF functionality, given the fact that in 2015 most of the communication-enabled appliances are not yet part of a DR program - except for smart thermostats and energy management systems (as detailed in Task 2).

It is clear that the trend towards connected devices will have a significant impact on the business models, the roles, the sales channels and service channels in this market. Instead of a one-time contact (sales) with the customer, the manufacturer/vendor/service provider will in the IoT scenario have a permanent link with the customer for the entire lifetime of the product. Adding the DSF functionality will bring more opportunities for improving existing services and/or extending to new services valorising the benefits to the energy system.

[19] Most of these 'smart' appliances or devices come with a smartphone or tablet app, which is indicated as 'app-enabled'.

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