Energy storage in Spain: forecasting electricity excess and assessment of Power-to-Gas potential up to 2050

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- The potential Spanish electricity excess is evaluated up to the year 2050
- Results depend on the assumed renewable production pattern and demand scenario
- The annual surplus for the year 2050 might vary between 1.4 TWh and 13.5 TWh
- The Power-to-Gas capacity required to store it would be in the range 7.0 – 19.5 GW

Energy storage in Spain: forecasting electricity excess and assessment of Power-to-Gas potential up to 2050

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Abstract

Innovative technologies and strategies to decarbonize electricity generation, transport, and heat supply sector are key factors to achieve the global climate targets set by international organizations. One of these strategies implies a significant increase of the share of renewable electricity in the energy mix. Given the intermittent behaviour of renewable energy sources (RES), a detailed assessment of future energy scenarios is required to estimate the potential surplus in electricity production. To facilitate the penetration of renewable energy sources up to significant shares, massive long-term electricity storage technologies must be considered. Among these technologies, power-to-gas (PtG) systems may foster the fossil fuels switch by providing storage of surplus renewable electricity in the form of hydrogen or synthetic natural gas. Thus, this energy carrier could be reconverted to electrical power to cover peak demand periods. In this work, a study of the prospective Spanish scenario is presented and the potential of PtG technology is assessed in terms of expected renewable surplus. We found that the annual electricity surplus for 2050 might vary between 1.4 TWh and 13.5 TWh, and the

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required PtG capacity would be in the range 7.0 – 19.5 GW, depending on the renewable production pattern and the increment of demand.

Keywords

Electricity storage, electricity surplus, forecast, Power to Gas, Spain

1. Introduction

In 2009, the European Renewable Energy Directive (2009/28/EC) [1] established the global policy to achieve renewable shares of at least 20% by 2020 in the European final energy consumption and a share of 10% in the sector of transport. Since each European country presents different available resources and its own energy market, the individual national targets are independently set (although always aligned with the European regulation). In this context, the Spanish Royal Decree 661/2007 of the 25th of May regulated electrical energy production under special regimes and provided a draft version of the Renewable Energy Plan 2011-2020 (REP 2011-2020). The derived Spanish National Renewable Energy Action Plan 2011-2020 (NREAP) is currently applied to meet the legally binding 2020 European targets in Spain.

The increase of the renewable share in the electricity production brings along with fluctuating surplus of power that limits the operational predictability and flexibility of the electricity network. Therefore, energy storage techniques have revealed as essential factors in future green electricity systems, to smartly manage the intermittent renewable power. Current storage techniques (pumped hydroelectric energy storage, compressed air energy storage, flywheels, batteries and thermal energy storage) present limited storage potentials related to their characteristic discharge times or energy storage densities [2]. Thus, Power to Gas (PtG) was proposed in the last years as a very promising storage technology to overcome these problems. PtG stores renewable electricity by converting a mixture of H_2 (from water electrolysis) and CO_2 into synthetic natural gas (SNG), which can be stored and easily distributed through the national natural gas network [3].

Several studies have already assessed the inclusion of PtG in the electricity systems of countries from central and northern Europe. Most of them analyse the German case, for which economic assessments are presented regarding Power to Gas and Power to Liquid systems [4][5]. Under a 85% renewable energy scenario in Germany, Jentsch et al. estimated the economical optimum for a PtG capacity implementation between 6 GW and 12 GW [6]. Schneider and Kötter thoroughly studied the existing geographical restrictions to install PtG facilities in the German state of Rhineland-Palatinate, and extrapolated the result to the whole country [7]. They determined the maximum PtG capacity that can be implemented in the country as 15.4 GW. Steubing et al. built a spatial model which identifies optimal bioenergy plant sizes and locations in Switzerland [8]. This work could be further widen to include the assessment of economically and environmentally optimal location of PtG fed by wood-based syngas in the country. Qadrdan et al. modelled the impact of integrating the British gas and electricity national grids through Power to Gas [9], given the large wind power capacity expected to be installed in the northern parts of England and Wales. They found that the operation cost of the grid would be reduced in 11% and wind curtailment could be reduced between 27% and 62% depending on demand. In this case, PtG capacity to be installed would range between 5 and 12 GW. Reiter and Lindorfer showed that the available CO_2 sources in Austria are enough to store in the form of methane all the national excesses of electricity generation from photovoltaics and wind power [10]. The biogas upgrading facilities are pointed out as the most suited ones for PtG integration since they present the lowest cost and the shortest distances to RES. Other alternative sources of CO_2 like power plants and refineries would be required since the amount of CO_2 generated from biogas plants is relatively low.

The increasing interest of southern European countries in PtG technology makes necessary the development of new studies of prospective scenarios. This study presents estimations of excess of electricity which might be stored under future Spanish energy scenarios. First, the evolution of the Spanish electricity system in the period 2020-2050, in terms of power capacity, energy production, and demand is estimated. Then, this model is used to analyze the amount of renewable electricity that could exceed the demand under different renewable generation patterns, and to estimate the PtG power capacity required to store it. Therefore, the aim of this study is to develop an energy system model representing future Spanish electricity generation, demand and constraints of the energy mix. Finally, based on the obtained results, Power to Gas capacity that could be installed in Spain for the next decades has been estimated.

2. Spanish electricity system

First official data of Spanish electricity system date from 1901 and it registered an installed power capacity of 78.2 MW that included hydropower (39%) and thermal power (61%) [11][12][13]. Since then, the energy system has been continuously transformed as a consequence of social evolution, but also affected for different historical milestones such as Civil War (1936 – 1939), droughts, the oil crisis of 1979, the application of European and national regulations, the introduction of renewables sources, and the Great Recession.

During the last decade of the XX century, the Spanish generation mix barely changed. Only combined heat and power (CHP) facilities grew significantly during this period. Afterwards, combined cycles and wind power rose rapidly to satisfy the increasing demand and reduce CO_2 emissions related to coal power (Figure 1). Nowadays, even though demand has decreased and subsidies to green electrical production have been cut back, RES have still experienced an increment of their share in the electricity market as a consequence of their cost reduction and improved competiveness (Figure 2).

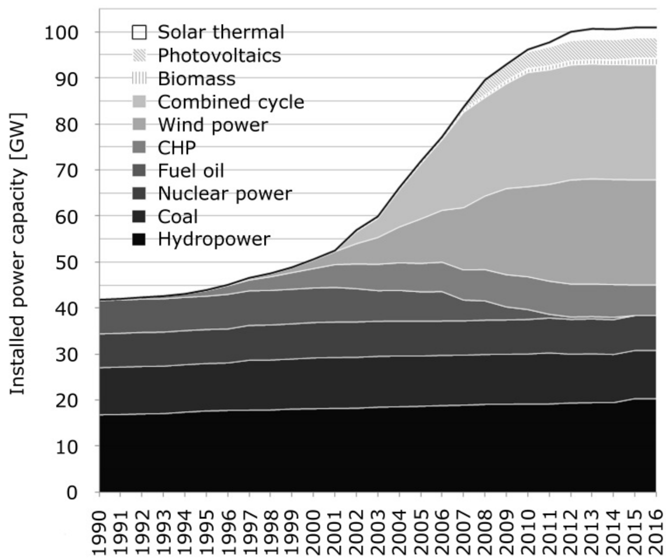

Figure 1. Installed power capacity in mainland Spain (1990 – 2016). Data from [14]

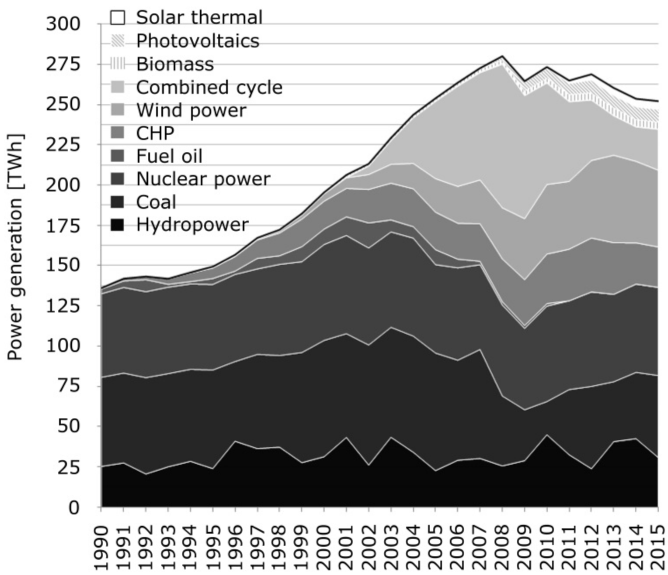

Figure 2. Power generation in mainland Spain (1990 – 2015). Data from [15]

Hydropower is a consolidated technology in Spain with 20.3 GW of installed capacity [14] distributed among over 870 plants [16], and whose estimated potential reaches 33 GW [17]. However, large projects are not expected to be launched in the short or mid-term [18], due to the lack of knowledge about available water resources (last evaluation was in 1980) [19] and the long periods required to process construction and operation licenses (6 years in average) [20]. Studies indicate a moderate development for the coming decades based on already existing infrastructures, through the implementation of water turbines in irrigation dams, retrofitting plants or renovating equipment. Therefore, although hydropower will slowly increase, its share in the energy mix will progressively be reduced in comparison to other RES with greater growing potentials [21].

There are not projected plans of increasing installed capacity of nuclear power in the mid-term. The seven plants commissioned between 1983 and 1988 (about 1 GW each) still participate in the energy market with average annual operating hours above 7700

[22]. According to their licenses terms, all of them should shut down between 2020 and 2024 [22][23]. Nevertheless, under favorable statements, the Ministry of Industry and Economy may issue periodic licenses renewals of 10 years [24]. In fact, since Spanish electricity system cannot deal with their removal in the short- or mid-term, the lifetime of nuclear plants will probably be extended up to 60 years (until 2043 – 2048) or even be unlimited as happened in other countries [25].

Coal participation in energy mix has been strongly reduced from 2007 onwards but the installed capacity has barely changed. Traditionally, coal power acted as backup technology to cover electrical demand given the limited flexibility of nuclear power and hydropower. Nowadays, the backup role is mainly covered by combined cycles, which exhibit much lower specific emissions of CO_2 (see Figure 2). The Spanish Government aims to promote during the next years the consumption of national coal up to annual participations of 7.5% in the energy mix. This strategy reduces energy dependence and instabilities caused by the variations in the price of imported fuels [26]. Contrary, prospective scenarios attending the restrictive environmental regulations which limits NO_X emissions would lead to 10.3 GW of installed capacity in 2020 [27]. Finally, carbon capture technologies could soften the progressive reduction of coal share, but they are not expected to be reliable before 2030 [28].

Currently, fuel oil in Spain only works in the islands because of their limited electric network and interconnections. In the mainland, the installed capacity of fuel oil has been substituted by other sources with better economic and environmental performances.

CHP facilities are present in more than 600 companies. Chemical, paper, and food industries contribute with the 50% of the total power production by means of CHP facilities. Given its dependence on industry, the development of CHP technology was slowed down in the last years as a consequence of the Great Recession. In order to reverse this situation, the Spanish CHP association projects to invest 1500 M€ for increasing the efficiency of more than half of installed capacity [29].

Combined cycles were introduced in Spain in 2002. By 2007 they had already become the technology with the largest installed capacity in the country. This uncontrolled expansion has led these facilities to be underused with annual hours of operation below 1000 h –16 plants out of 49 are not economically feasible– [30]. So, progressive shutdowns are expected to occur whenever the closure is authorized.

Considering a sustainable exploitation of resources, the maximum potential for biomass power would lay in the range 3 – 5 GW [31]. However, social and technical barriers associated to biomass power were underestimated (e.g., variety of crops, fuel dispersion, support from industry) and installed capacity does not achieve the 3 GW. In 2030, the expected share of biomass would be around 5 % of total production [32].

In 2010, solar thermal power installed in Spain accounted for the 60% of worldwide capacity. The installation of more than 15 GW was projected under the subsidized renewable regime, but only 2.4 GW were finally installed [33]. Therefore, between 4.8 GW and 10 GW of installed capacity are expected for 2020 [33][34]. Given the high stability of thermal solar operation associated with thermal energy storage, its development in long-term scenarios with high renewable shares could be promoted. Thus, 20 GW are expected as a desirable capacity for 2050 [35].

In 2008, photovoltaic power experienced the greatest annual growth with an increment of 60% of installed capacity [14]. The large subsides given to PV (12 times the corresponding one to wind power production) leaded to an accelerated proliferation of new facilities which in numerous occasions were underqualified and rapidly began to deteriorate [31]. Nowadays, the radical reduction of subsides has broken the expansion trend and the expectative of 7.25 GW installed capacity will probably be achieved beyond 2020 [33].

Finally, wind power has become the RES with the largest installed capacity in Spain, which generated in 2013 about 1.17 TWh of surplus power [36]. The maximum potential of on-shore wind installed capacity would amount to 151 GW once protected and unprofitable areas are removed [37]. In practice, total capacity is expected to rise up to 24 GW for 2020, whilst repowering could contribute by adding 5 GW in mid-term [31]. Additionally, growth potential concerning off-shore wind power is estimated between 5 GW and 8.5 GW [37].

3. Methodology

The definition of a future scenario for the Spanish electricity system has to consider both the predicted energy demand and the expected electricity production. The prediction of energy demand evolution is based on the results provided by '*The Global Calculator*', a useful tool developed by the International Energy Agency which has been previously validated. This tool models the world's energy, land and food systems to explore future scenarios [38]. Then, the energy production is calculated as the product of the estimated installed power capacity and the operating hours, which are heuristically inferred from the analysis presented in Section 2. Since demand and production are established separately, additional restrictions were imposed to validate the feasibility of these scenarios (Figure 3). The installed capacity forecast provided by

Spanish institutions gives reliability to the defined scenarios while restrictions guarantee the technical consistency.

Once the future scenario is established, the energy storage potential may be obtained as the difference between the potential production and the expected demand throughout time. The first step in this calculation process is the determination of the time-discretization unit that will better fit with this type of analysis. We could discretize the year in periods that span between an hour (minimum period of time considered in Spanish energy market) and a year. An hourly interval would be unnecessarily accurate since a long-term estimated scenario will probably introduce significant deviations from real hourly patterns of electricity production and demand. On the contrary, monthly and longer periods would not allow the detection of energy surplus situations. Therefore, a daily discretization is used in the model.

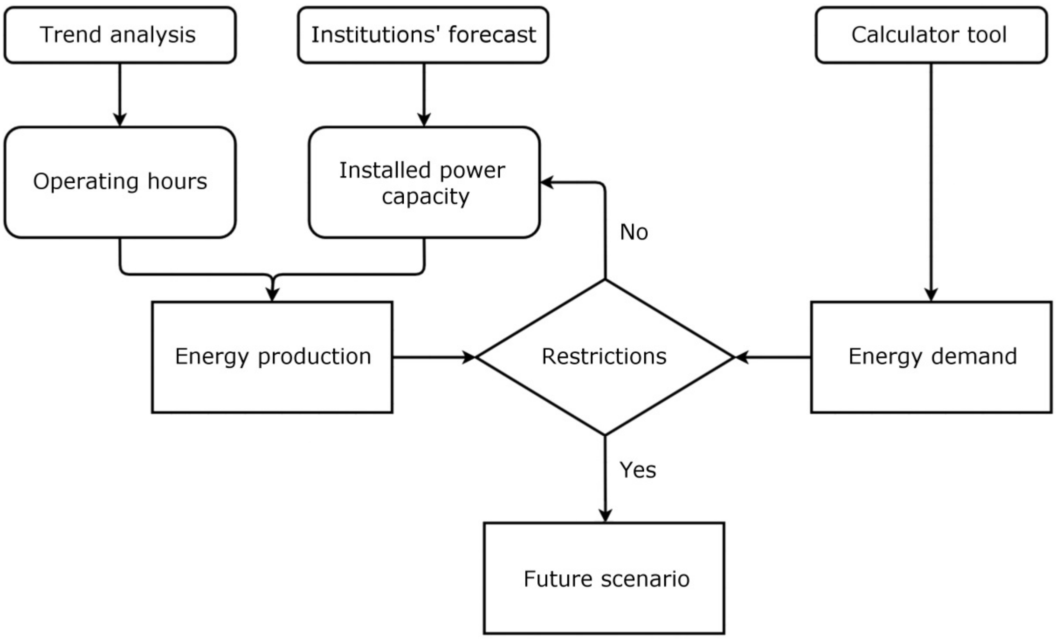

Figure 3. Model flow chart.

3.1. Energy demand scenarios

The estimation of future electricity demand is done based on results provided by *The Global Calculator* tool [38], funded by the UK Government's International Climate Fund and the EU's Climate-KIC. This tool incorporates a model of the world's energy, land and food systems to explore the future thermal requirements, electrical power demand, or greenhouse gas emissions. The possible scenarios depend on multiple variables like social habits, industrial investments, or policies (Annex A).

Several potential situations were evaluated and all of them can be framed within two significant scenarios with different growth rates of electricity demand. In Scenario 1, the demand moderately increases 1.36% per year, whilst in Scenario 2 the annual growth rate is 1.73% (Figure 4).

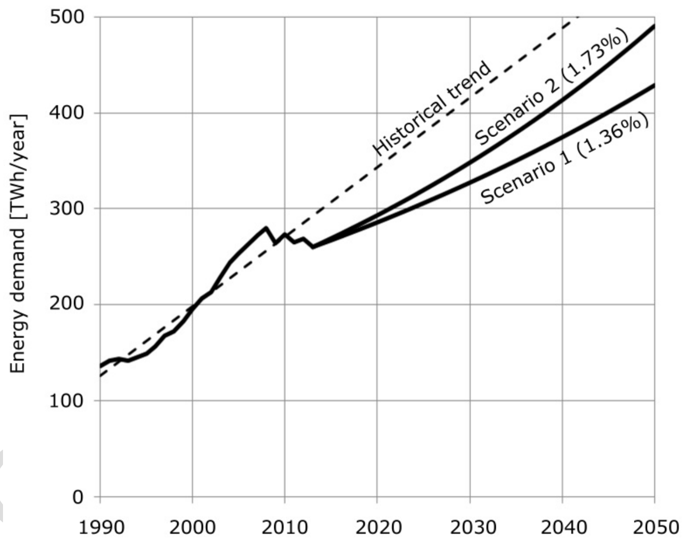

Figure 4. Energy demand scenarios for the electricity system. Historical data from [15]

In both scenarios, the increment of the global mean temperature by the year 2100 would be restricted to 2ºC. The main social assumptions considered in *The Global Calculator* tool that will lead to the achievement of the 2ºC scenario are: (i) the increase of average occupancy in cars and trains by a 15%, (ii) the limitation of building temperatures at 18ºC and 26ºC during winter and summer respectively, and (iii) a significant promotion of recycling.

To achieve a moderate growth of electricity demand (i.e., Scenario 1), investments must be focused on improving the efficiencies of fossil power plants, paper and cement industries, instead of on electrifying the transport. Furthermore, appliance efficiency and treatment of wastes and residues are also crucial to keep annual demand growth around 1.36%.

3.2. Operating hours

The operating hours of renewable and nuclear energy sources are estimated through a deep analysis based on historical data of the last decade, current energy Spanish policies and technology maturity (Table 1). Since fossil plants act as backup power, the share of renewable sources in the electricity system will also determine the fossil necessities. The operating hours of fossil fuel power plants in the model must also fulfil the specific restrictions established in Section 3.3.

Four general trends are easily distinguished when historical data of operating hours are represented (Figure 5). Wind power, hydropower, small hydro, and nuclear power have become mature technologies that operate steadily on average (Figure 5a). Photovoltaics and solar thermal energy rose rapidly in a 2 – 3 years period coming to a stagnant between 1800 – 2000 hours (Figure 5b). CHP and biomass power plants have slowly increased their operation since 2002 (Figure 5c). Lastly, coal power plants and combined cycle plants have reduced their operating hours to counterbalance the increase of renewable sources from 2007 onwards (Figure 5d).

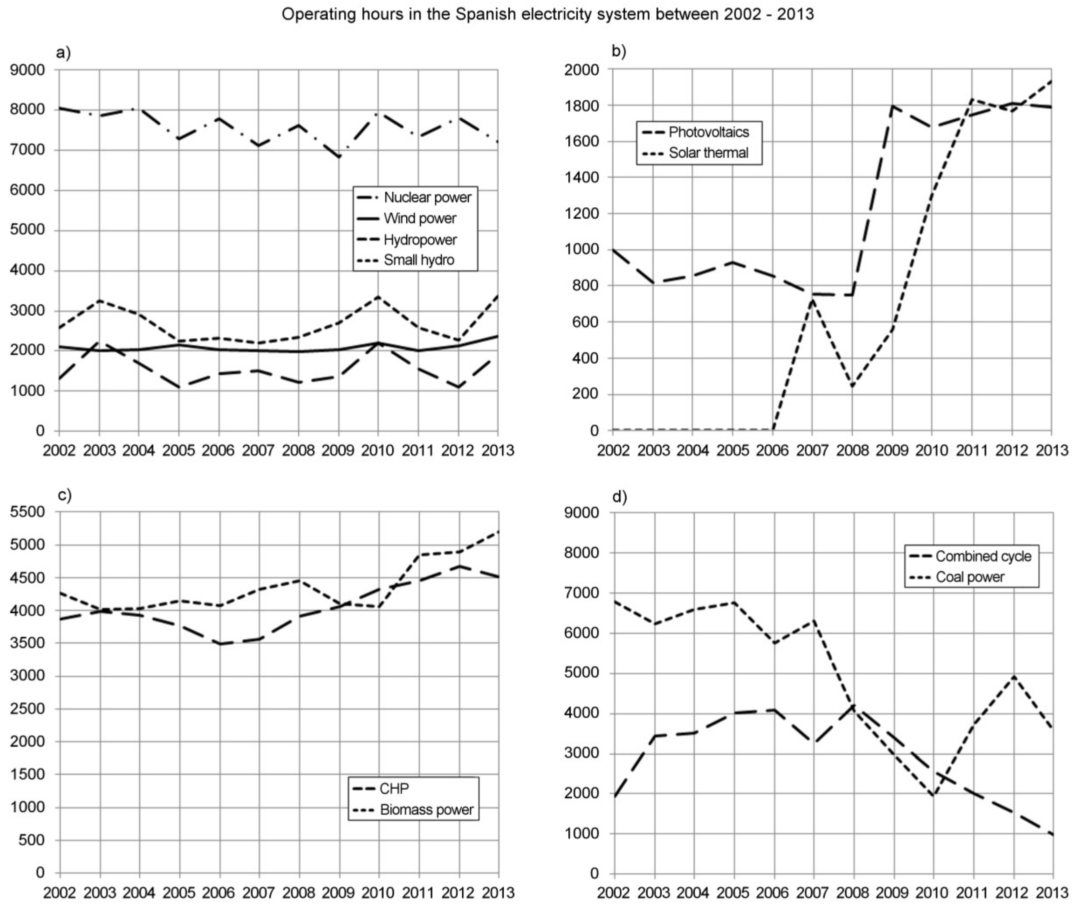

Figure 5. Operating hours [h] in the Spanish electricity system (2002 – 2013) [39].

Hydropower and small hydro remain stable with periodic fluctuations according to natural, wet and dry environmental cycles. Fuel replacement in nuclear plants produces periodic oscillations in annual operation. Unplanned shutdowns of nuclear plants get more and more frequent –all of these plants date from before 1988– slightly diminishing the average number of operating hours [40].

Wind power operates nearly over 2000 annual hours, mostly due to weather conditions but also as a consequence of Government's policies that limit benefits to renewable generation. In the period 2010 – 2014, wind power received subsides only for the first 2350 hours of operation [41]. Photovoltaics case is illustrative since operating hours swiftly grew up to the maximum number of subsidized operation hours [42]. Nowadays, subsidizes to renewable energy sources are individualized and progressively cut, so their operation hours are expected to rise [43][44]. Lastly, restrictions to solar thermal power started from 2350 hours, not affecting the increase of operating hours [41]; whilst CHP and biomass power were not even limited. Therefore, operating hours of solar thermal, CHP and biomass would increase according to the technology development.

Table 1. Estimation of operating hours [h] in the future Spanish electricity system.

	2020	**2030**	**2040**	**2050**
Hydropower	1600	1620	1640	1660
Small hydro	2700	2720	2740	2760
Wind power	2450	2600	2650	2700
Photovoltaics	1850	2000	2300	2650
Solar thermal	2200	2600	3050	3500
Biomass	5500	6000	6350	6750
CHP	4700	5000	5300	5600
Nuclear power	7200	7000	6850	-

3.3. Restrictions to the energy mix model

The estimation of the Spanish electric power system derived from our model is kept as close as possible to the distribution presented in Section 2. However, some restrictions are imposed to the initial defined scenario in order to achieve a coherent final scenario. These restrictions are:

- Whenever backup power is required, biomass based power plants will have preference against fossil fuel power plants.
- Coal share is maintained at 7.0% – 8.0% in 2020 [26], and then progressively diminished.

- The participation of combined cycles varies depending on the availability of renewable energy sources.
- Installed backup capacity (biomass, coal and natural gas) must be able to satisfy electricity demand when the availability of renewable power is reduced to 45% and availability of base power (nuclear and CHP) to 95%.

A key aspect to be considered when sizing the energy mix is the fact that backup capacity must be operated a minimum number of hours to ensure its economic feasibility. This implies that existing nuclear plants should be operated beyond 2050, instead of being replaced by renewable power. Otherwise, the required backup power would be excessively underused.

3.4. Energy demand time-pattern

In order to identify electricity surplus situations, the annual demand must be distributed throughout each day of the year. This distribution is done based on historical data, since energy demand mainly depends on sociological aspects related to lifestyle, festivities and seasons, which barely vary in long-term. We have summarized the annual period in a list of day-types together with their average annual needs between 2010 and 2013 (Table 2) [45]. The values are presented in Table 2 as the percentage of the total annual demand that the daily demand represents. Thus, future daily demand is calculated considering the type of day and the total annual demand.

Table 2. Average daily demand (annual percentage) [%] throughout years 2010 – 2013 [45].

Day	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
Working day (1st half-month)	0.3036	0.3145	0.2924	0.2695	0.2765	-	0.2992	0.2772	0.2800	0.2765	0.2788	-
Working day (2nd half-month)	0.3220	0.3060	0.2838	0.2695	0.2844	-	0.2992	0.2940	0.2800	0.2607	0.2952	-
1st Saturday	0.2484	0.3060	0.2666	0.2541	0.2291	0.2400	0.2728	0.2436	0.2400	0.2449	0.2460	0.2816
2nd Saturday	0.2852	0.2890	0.2580	0.2541	0.2370	0.2400	0.2640	0.2436	0.2400	0.2291	0.2460	0.2640
3rd Saturday	0.2852	0.2720	0.2408	0.2310	0.2449	0.2400	0.2552	0.2604	0.2400	0.2291	0.2460	0.2904
4th and 5th Saturday	0.2852	0.2805	0.2580	0.2310	0.2449	0.2400	0.2552	0.2604	0.2400	0.2449	0.2624	0.2728
1st Sunday	0.2392	0.2805	0.2494	0.2156	0.2054	0.2320	0.2552	0.2184	0.2240	0.2212	0.2378	0.2552
2nd Sunday	0.2576	0.2720	0.2408	0.2233	0.2370	0.2320	0.2376	0.2184	0.2240	0.2212	0.2542	0.2552
3rd Sunday	0.2760	0.2550	0.2408	0.2310	0.2291	0.2320	0.2376	0.2268	0.2240	0.2054	0.2378	0.2640
4th and 5th Sunday	0.2668	0.2720	0.2236	0.2079	0.2212	0.2320	0.2376	0.2352	0.2240	0.2291	0.2460	0.2376
New Year (1st Jan.)	0.2300	-	-	-	-	-	-	-	-	-	-	-
Epiphany (6th Jan.)	0.2576	-	-	-	-	-	-	-	-	-	-	-
Maundy Thursday	-	-	-	0.2310	-	-	-	-	-	-	-	-
Good Friday plus weekend	-	-	-	0.2233	-	-	-	-	-	-	-	-
Workers' Day (1st May)	-	-	-	-	0.2133	-	-	-	-	-	-	-
Assumption of Mary (15th Aug.)	-	-	-	-	-	-	-	0.2352	-	-	-	-
National Day (12th Oct.)	-	-	-	-	-	-	-	-	-	0.2291	-	-
All Saints' Day (1st Nov.)	-	-	-	-	-	-	-	-	-	-	0.2214	-
Constitution's Day (6th Dec.)	-	-	-	-	-	-	-	-	-	-	-	0.2816
Immaculate Conception (8th Dec.)	-	-	-	-	-	-	-	-	-	-	-	0.2464
Christmas Eve (24th Dec.)	-	-	-	-	-	-	-	-	-	-	-	0.2728
Christmas (25th Dec.)	-	-	-	-	-	-	-	-	-	-	-	0.2376
New Year's Eve (31st Dec.)	-	-	-	-	-	-	-	-	-	-	-	0.2288
Working day (last week of June)	-	-	-	-	-	0.2960	-	-	-	-	-	-
Working day (week of 6th Dec.)	-	-	-	-	-	-	-	-	-	-	-	0.2992
Working day (after 25th Dec.)	-	-	-	-	-	-	-	-	-	-	-	0.2376
Working day (rest)	-	-	-	-	-	0.2720	-	-	-	-	-	0.3080

3.5. Energy production time pattern

Energy demand does not affect generation patterns as shown in Table 3, where monthly distribution of annual electricity production by technology is presented. Hydropower, wind power and solar power are weather-dependent, presenting seasonal productions. CHP facilities linked to industrial processes have a stable monthly power production which is only reduced in August due to the summer break. Nuclear provides base-load power. Nuclear power production is occasionally reduced due to fuel replacement in the reactors or unexpected shutdowns. Similarly, biomass plants work steadily, since they are still emerging in Spain. Lastly, fossil fuel power plants operate as back-up suppliers to match production and demand.

Table 3. Average monthly production [%] 2008 – 2013 [39].

	Hydropower	Wind power	Photovoltaics	Solar thermal	Biomass	CHP	Nuclear
Jan.	11.2	9.6	4.9	2.4	8.3	8.7	8.9
Feb.	9.8	9.8	6.5	4.2	7.7	8.1	8.4
Mar.	11.2	9.7	7.9	4.6	8.0	8.7	8.7
Apr.	10.7	8.3	8.9	6.2	8.1	8.3	8.1
May	9.6	7.6	10.7	9.9	8.1	8.4	7.4
June	8.1	6.6	10.8	12.5	8.1	8.1	7.6
July	6.7	6.4	11.8	15.9	8.7	8.5	8.7
Aug.	5.6	6.4	10.9	14.8	8.5	7.1	9.4
Sep.	4.5	6.3	9.2	12.2	8.2	8.3	8.7
Oct.	5.3	7.7	8.0	8.7	8.7	8.6	8.3
Nov.	7.6	10.6	5.5	4.3	8.6	8.6	7.7
Dec.	9.7	11.0	4.9	4.3	9.0	8.6	8.1

According to reviewed data, daily energy production is constantly distributed during the month except for wind power, which presents a daily chaotic distribution. Therefore, the model assumes that the monthly power production by means of solar and hydro technologies (Table 3) is homogeneously distributed among the days of every month.

Besides, the estimation of electricity production from nuclear and CHP is simplified by considering constant monthly and daily distribution.

The model only considers daily fluctuations for wind power generation given its strong variability [45]. Hence, calculations are performed by using historical wind production patterns between 2009 and 2013. A range of possible daily wind productions is derived from these historical data. The utilization of an average value for the daily production would have eliminated the intrinsic irregularities and the daily peak production of wind power.

Biomass, coal and natural gas do not present specific patterns since they act as backup technologies to match production and demand when the rest of energy sources do not cover the power needs.

4. Results

The applied methodology identifies those periods with electricity surplus production by using the daily differences between production and demand. The following results show the obtained estimations for the energy scenarios of the years 2020, 2030, 2040 and 2050.

4.1. Installed power capacity and generation

The proposed scenarios essentially differ in the electrical demand growth rates. The power requirement of each scenario leads to different proposals for the Spanish energy mix (Table 4 and Table 5). The moderate annual increment of electricity demand (1.36% - Scenario 1) may be covered by the installed power capacity defined in Section 2. Thus, the electricity production from CHP is doubled in 2050, small hydro participation increases up to 4.0% – 4.5%, and biomass installed capacity reaches 5GW.

However, higher annual growth (1.73% - Scenario 2) will require larger installed capacity to satisfy electrical demand.

Under both scenarios, the nuclear technology must continue in operation at similar load levels. From an economic point of view, the nuclear base load cannot be replaced by renewable energy sources since the required installed capacity of backup power would be extremely high and consequently underused. The participation of coal power and combined cycles remains below 2200 hours even when nuclear plants operates 7300 hours and 6000 hours for Scenario 1 and 2 respectively (Table 6).

The participation of wind power and natural gas in the electricity production is given as ranges related to historical wind patterns. A worse agreement between electricity demand and wind power production implies a greater potential for energy storage, also increasing the required share of natural gas in the energy market.

In 2050, renewable energy sources provide more than 63% of energy production, while fossil fuels fall below 11%. Moreover, surplus power may range between 1.4 TWh and 13.5 TWh depending on the electrical demand and the pattern of wind power.

Table 4. Installed power capacity [GW] in the future Spanish electricity system.

	Demand growth rate: 1.36%				**Demand growth rate: 1.73%**			
	2020	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Hydropower	17.9	18.1	18.6	19.2	17.9	19.6	21.7	23.9
Small hydro	2.4	3.8	6.1	6.4	2.4	3.7	4.2	4.7
Wind power	26.0	28.7	32.1	35.8	24.5	32.6	39.8	44.4
Photovoltaics	5.4	7.3	8.2	9.1	5.4	7.3	9.8	15.7
Solar thermal	10.6	13.2	16.4	20.3	9.7	13.0	17.5	23.6
Biomass	1.2	2.8	3.8	5.3	1.2	2.0	3.5	6.2
CHP	8.1	9.9	10.8	11.6	8.1	10.8	13.2	16.1
Nuclear power	7.9	7.9	7.9	6.1	7.9	7.9	8.4	8.1
Coal power	10.4	9.4	9.0	8.6	10.4	9.3	7.6	6.9
Combined cycle	24.2	22.5	21.4	20.4	24.2	22.5	21.4	20.4
Total	**114.1**	**123.6**	**134.3**	**142.8**	**111.7**	**128.7**	**147.1**	**170.0**

Table 5. Energy production [TWh] in the future Spanish electricity system.

	Demand growth rate: 1.36%				Demand growth rate: 1.73%			
	2020	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Hydropower	28.7	29.3	30.6	31.9	28.7	31.8	35.5	39.7
Small hydro	6.4	10.4	16.6	17.7	6.4	10.0	11.5	12.9
Wind power	63.2 – 60.9	74.3 – 70.5	84.0 – 80.2	95.2 – 91.4	59.9 – 58.6	84.3 – 79.9	103.0 – 96.9	113.8 – 106.4
Photovoltaics	10.1	14.6	18.9	24.1	10.1	14.6	22.6	41.6
Solar thermal	23.3	34.2	49.9	71.2	21.3	33.9	53.5	82.4
Biomass	6.7	16.7	23.9	35.9	6.7	12.0	22.1	41.5
CHP	38.3	49.6	57.0	65.2	38.3	54.2	70.0	90.2
Nuclear power	56.6	55.1	53.9	44.7	56.6	55.1	57.3	48.7
Coal power	22.9	19.6	18.7	17.2	20.5	13.9	6.2	4.9
Combined cycle	30.0 – 32.3	23.5 – 27.3	21.3 – 25.1	26.0 – 29.8	45.0 – 46.3	38.6 – 43.0	31.9 – 38.0	15.2 – 22.6
Total production	**286.2**	**327.3**	**374.8**	**429.1**	**293.5**	**348.4**	**413.6**	**490.9**
Surplus power	0.49 – 2.80	0.45 – 4.20	1.02 – 4.79	1.41 – 5.24	0.17 – 1.44	0.51 – 4.90	2.46 – 8.60	6.10 – 13.54

Table 6. Operation hours of fossil sources [h] in the future Spanish electricity system.

	Demand growth rate: 1.36%				Demand growth rate: 1.73%			
	2020	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Coal power	2204	2080	2084	2005	1980	1500	817	715
Combined cycle	1243 - 1338	1045 - 1212	995 - 1171	1277 - 1466	1865 - 1917	1716 - 1911	1489 - 1775	745 - 1110

4.2. Electricity storage potential

The daily distributions of demand and production along the year allow the calculation of the surplus power and the identification of those periods with greater storage potential. Besides, the historical patterns of wind power generation are used to establish the minimal and maximum reasonable limits for the estimated surplus.

Potential storage situations were mainly found within the period from March to June. In fact, surplus power is guaranteed in April and May regardless of the year and scenario.

December presents strong variability depending on the agreement between the commonly high renewable production and the decay in electricity demand during the last week of the year. In contrast, January and February might present a lack of energy excess in 2050 even under situations of high shares of renewable power in the energy mix (Figure 6).

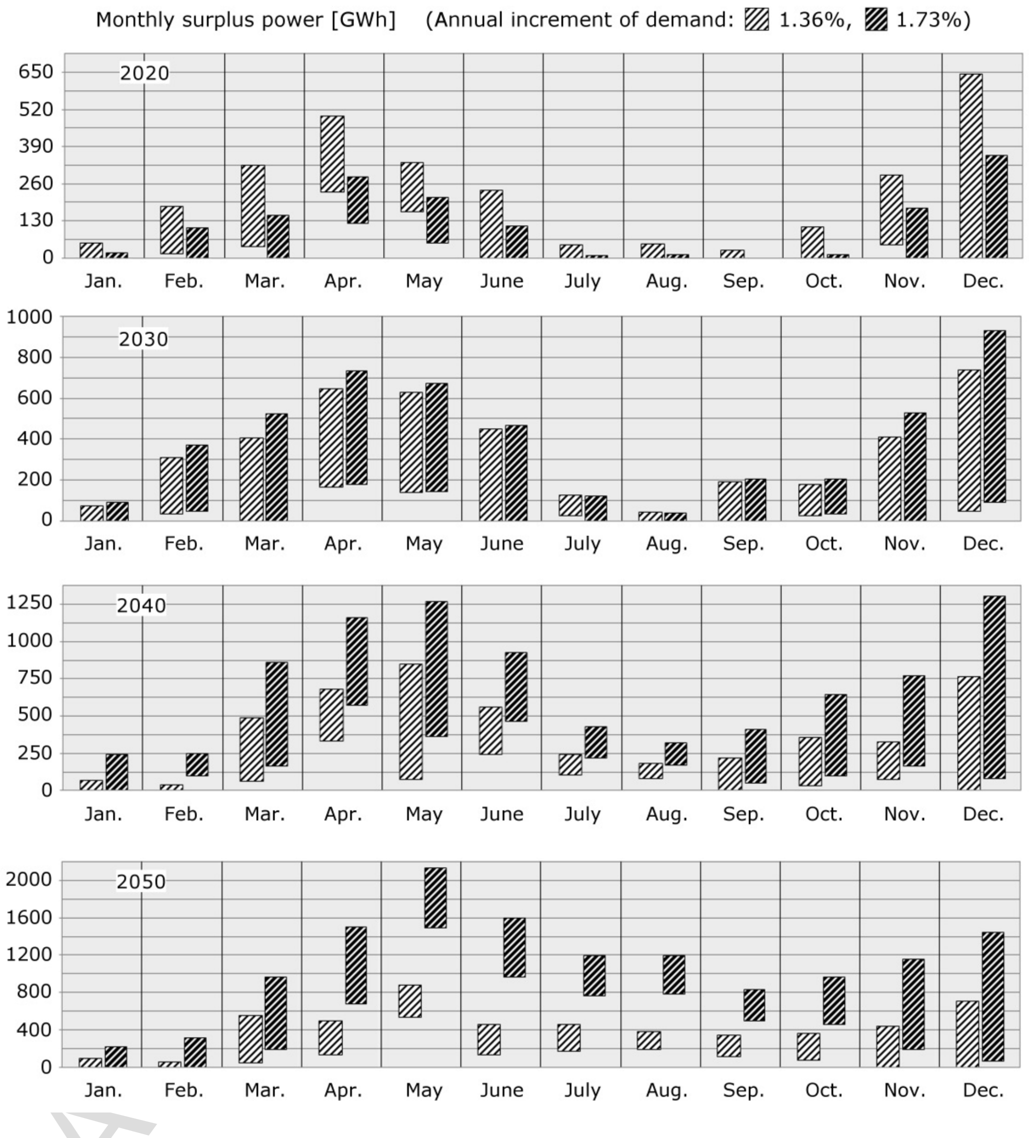

Figure 6. Ranges of possible monthly surplus energy [GWh] in the future Spanish electricity system.

4.3 Power to Gas potential conversion capacity

Electrical energy storage is one of the key technologies identified to meet challenges derived from the future energy scenarios with renewable electricity surpluses. These systems store energy in a certain state –according to the technology used– to be later reconverted into electrical energy when demanded. There exists a wide variety of options with complex characteristics. Given the long-term and great power capacity of Power to Gas technology, it appears as one of the most promising options for massive storage in national electric systems [46].

Results of electricity potential storage presented in the previous section are now used to size the required Power to Gas capacity to process the whole energy surplus. In energy systems characterized by base loads around 20 GW and high shares of wind power (as the predicted Spanish system), electricity surplus behaves smoothly with hourly peaks that rise up to the 8% of the daily excess [47]. Therefore, maximum capacity to be installed should be able to process in an hour the 8% of the highest daily surplus power. However, an installed PtG capacity able to process the 100% of energy surplus would be underused, since we could process even the 90% of annual excess with less than the half of that capacity (Figure 7).

Thus in Scenario 1, a suitable option for the Spanish electricity system is to install 10.5 GW of PtG in 2040, and then reach 13.0 GW in 2050. These values would guarantee the storage of over 90% of excess power regardless of the wind pattern. Besides, if the agreement between demand and wind production is favourably matched, the power capacities needed to process the 90% of excess could be reduced down to 7.0 GW. In Scenario 2, processing the 90% of surplus power would require 15.0 GW in 2040 and

19.5 GW in 2050, although it could be as low as 8 GW and 14.5 GW if wind production adequately matches energy demand.

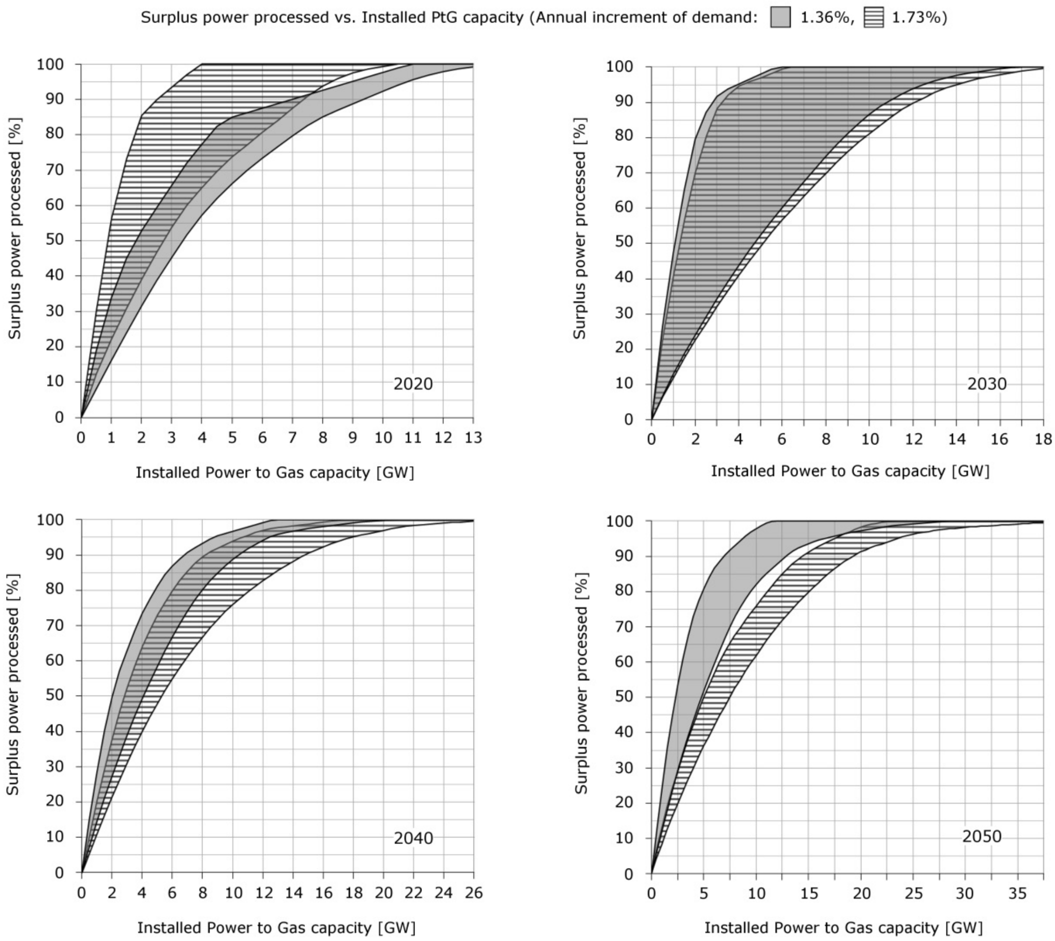

Figure 7. Surplus energy processed [%] as a function of installed Power to Gas capacity [GW].

The utilization of such technology would allow to valorize the electricity surplus at the same time that frequent curtailments in wind farms would be avoided. Besides, the electrical transmission congestion could be suitably managed by this large-scale electricity storage, what would soften the stress over system operators [48]. If Power to Gas plants are located near the renewable power plants, ohmic losses and transmission congestion are avoided, since energy could be easily transmitted through the natural gas network as methane. This kind of economic advantages have already been proved in the largest worldwide Power to Gas plant (6 MW), which was recently qualified for participating in the German electricity balancing market [49].

The international export of electricity between European countries is not an option when a global scenario of high renewable share is approached, since near countries will have electricity surplus at the same periods. Electricity is required to be displaced in time instead of in space, so massive electricity storage should act as a local solution adapted to each country. Besides, transmission congestion might be relevant during international energy trades [50].

3. Conclusions

The prospective renewable energy surplus and the derived Power to Gas potential have been assessed for the Spanish case up to the year 2050, on the basis of historical data, current policies, technology maturity, and growth forecast from Spanish institutions. Two possible scenarios of electricity demand were considered, which will require different installed power capacity. Depending on the national investment strategy, the annual increment on demand might be moderate (1.36%, Scenario 1) or high (1.73%, Scenario 2). Moreover, the resulting amounts of renewable electricity surplus have been estimated under different historical renewable generation patterns.

A moderate increment on demand (1.36%) will imply that the production from CHP is doubled, the small hydro participation increases up to 4.0% – 4.5%, and biomass installed capacity reaches 5GW by the year 2050, according to the forecast of the corresponding institutions. However, higher annual growth (1.73%) requires larger installed capacities to satisfy electricity demand. Under both scenarios, nuclear power must be operated beyond 2050. Such base load cannot be replaced by renewable energy sources since the required backup power would be extremely underused; even so, the participation of coal power and combined cycles lies below 2200 hours.

In 2050, renewable energy sources would provide more than 63% of the power production, whilst fossil fuels fall below to 11%. Thus, the annual amounts of renewable surplus would amount to 1.4 – 5.2 TWh for Scenario 1, and 6.1 – 13.5 TWh for Scenario 2, depending on production and demand matching. Potential storage situations are mainly found from March to June. Regardless of the scenario, surplus power is ensured in April and May. The required PtG capacities for processing the 90% of total excess would range between 7.0 and 13.0 GW for Scenario 1, and between 14.5 and 19.5 GW for Scenario 2. Similar conclusions are achieved in those studies for Germany and Great Britain.

Once these results have been determined, the optimal size and location of Power to Gas plants with regards to environmental and economic performance should be further assessed with a spatially explicit value chain model of the production of synthetic natural gas (SNG) from biological and catalytic methanation. This next step shall consist of several individual models for the availability, transportation, conversion of wastes, water and CO_2 to SNG and heat, and the use of these products to substitute non-renewable energy services. An optimization strategy should be applied to finally select the optimal technology configuration for the defined sizes and different locations for the required compromise between the environmental and the economic performance.

Annex A. Forecast of electricity demand.

The electricity demand trends are calculated based on information provided by the *Global Calculator* tool, funded by the UK Government's International Climate Fund and the EU's Climate-KIC. This tool allows the user to simulate the evolution of a number of environmental parameters as a function of a large amount of variables related to way of living, energy mix, demographics and so.

Table A.1 presents the definition of four scenarios which lead to different values of the electricity demand yearly increment: + 1.73%/year, + 1.36%/year, + 1.80%/year and + 1.40%/year. Two of them (+ 1.73%/year, + 1.36%/year) ensure the limitation of global temperature increase up to 2ºC by 2100 while the two others (+ 1.80%/year and + 1.40%/year) do not. The variables which define each scenario are gathered in fifteen categories: travel, homes, diet, transport, buildings, manufacturing, CCS, bioenergy, fossil fuel, nuclear, renewable, food, land use, demographics and emissions beyond 2050. In order to simplify the quantification of these variables for every scenario, each one may be only varied between 0-4 and each level is properly defined in the cited application (http://tool.globalcalculator.org/).

Table A.1. Definition of scenarios (variables and levels) related to different electricity demand increments.

Variable (Global calculator tool, version 2017)	Variable (Global calculator tool, version 2014)	Electricity increment: 1.73% /year 2ºC increment avoided: Yes	Electricity increment: 1.36% /year 2ºC increment avoided: Yes	Electricity increment: 1.80% /year 2ºC increment avoided: No	Electricity increment: 1.40% /year 2ºC increment avoided: No
TRAVEL					
Passenger distance	Passenger distance	2.0	2.0	2.0	2.0
Freight distance	Freight distance	2.0	2.0	2.0	2.0
Mode	Mode	2.2	2.2	2.0	2.2
Occupancy & load	Occupancy & freight load	2.5	2.5	2.0	2.5
Car own or hire	-	-	-	-	-

HOMES					
Temperature & hot water use	Temperature & hot water use	3.0	3.0	2.0	2.0
Lighting & appliance use	Lighting & appliance use	2.3	2.3	2.0	2.3
Building size	Building size	2.3	2.3	2.0	2.3
Product lifespan & demand	Product lifespan & demand	2.3	2.3	2.0	2.3
DIET					
Calories consumed	Calories consumed	2.0	2.0	2.0	2.0
-	Meat consumed	2.4	2.4	2.0	2.4
Quantity of meat	-	-	-	-	-
Type of meat	-	-	-	-	-
TRANSPORT					
Electric & hydrogen	Electric & hydrogen	3.0	2.0	2.0	2.0
Transport efficiency	Transport efficiency	3.0	3.0	2.0	3.0
BUILDINGS					
Building insulation	Building insulation	3.0	3.0	2.0	3.0
Temperature & cooking tech.	Temperature & cooking tech.	2.4	3.0	2.0	2.0
Appliance efficiency	Appliance efficiency	2.4	2.7	2.0	2.0
MANUFACTURING					
Design, materials & recycling	Design, materials & recycling	3.0	3.0	2.0	3.0
Iron, steel & aluminum	Iron, steel & aluminum	2.0	2.0	2.0	2.0
Chemicals	Chemicals	2.0	2.0	2.0	2.0
Paper & others	Paper & others	2.0	2.2	2.0	2.0
Cement	Cement	2.0	2.2	2.0	2.0
CARBON CAPTURE AND STORAGE					
CCS (manufacturing)	CCS (manufacturing)	3.0	3.0	2.0	2.0
CCS (electricity)	CCS (electricity)	3.0	3.0	2.0	2.0
BIOENERGY					
Bioenergy yields	Bioenergy yields	1.0	1.0	1.0	1.0
Solid or liquid	-	-	-	-	-
FOSSIL FUEL					
Coal / oil / gas	Coal (incl- biomass) / oil / gas	3.0	3.0	3.0	3.0
Fossil fuel efficiency	Fossil fuel efficiency	2.5	3.0	2.0	2.5
NUCLEAR					
Nuclear	Nuclear	2.0	2.0	2.0	2.0
RENEWABLES					
Wind	Wind	3.0	3.0	3.0	3.0
Hydroelectric	Hydroelectric	2.0	2.0	2.0	2.0
Marine	Marine	1.0	1.0	1.0	1.0
Solar	Solar	3.0	3.0	3.0	3.0
Geothermal	Geothermal	1.0	1.0	1.0	1.0
Storage & demand shifting	Storage & demand shifting	3.0	3.0	2.8	3.0
FOOD					
Crop yields	Crop yields	2.0	2.0	2.0	2.0
Wastes & residues	Wastes & residues	1.5	2.0	1.5	1.5
-	Livestock yields	2.0	2.0	2.0	2.0
Livestock (grain/residues fed)	-	-	-	-	-
Livestock (pasture fed)	-	-	-	-	-
LAND USE					
Land-use efficiency	Land-use efficiency	2.0	2.0	2.0	2.0
Surplus land (forest & bioenergy)	Surplus land (forest & bioenergy)	1.5	1.0	1.5	1.0
DEMOGRAPHICS					
Global population	Global population	2.0	2.0	2.0	2.0

Urbanization	Urbanization	2.0	2.0	2.0	2.0
EMISSIONS AFTER 2050					
Emissions trajectory	Emissions trajectory	2.0	2.0	2.0	2.0

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