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Impact of Smart Grid Technologies on Peak Load to 2050

INTERNATIONAL ENERGY AGENCY

STEVE HEINEN, DAVID ELZINGA, SEUL-KI KIM AND YUICHI IKEDA

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The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 28 member countries and beyond. The IEA carries out a comprehensive programme of energy co-operation among its member countries, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The Agency's aims include the following objectives:

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Acknowledgments

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This working paper is a first IEA effort in an evolving modelling process of smart grids. All questions and comments are appreciated and should be sent to:

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Summary

Peak load defines the generation transmission and distribution capacity of an electricity system, and also serves as important design metric for current and future electricity infrastructure needs. As electricity load changes throughout the day and the year, electricity systems (including generation, transmission and distribution) must be able to deliver the maximal load at all times. In reality, the infrastructure is thus underutilised during non-peak times.

This working paper analyses the evolution of peak load demand between now and 2050 in four key regions: OECD Europe, OECD North America, OECD Pacific and China. Demand for electricity is rising in all analysed regions as additional electric end-use technologies are adopted in various sectors such as transport, heating and cooling, and could potentially increase peak load

Smart grid technologies show strong potential to optimise asset utilisation by shifting peak load to off-peak times, thereby decoupling electricity growth from peak load growth. This working paper presents an on-going effort to develop a peak load modelling methodology and estimate the potential of smart grid technologies to reduce it.

Using a scenario-planning approach, possible projections are made for the four cases based on two main uncertainties: technology and policy support. Technology is modelled using the *Energy Technology Perspectives 2010* (*ETP 2010*) Baseline and BLUE Map Scenarios (IEA, 2010a). Smart grid policy support is assumed to be either minimum (SG_{MIN}) or maximum (SG_{MAX}).

The evolution of peak load is estimated for all cases by taking into account smart grid technologies. At this stage, smart grid functionalities are limited to the integration of electric vehicles and the deployment of demand response in the residential and service sectors. The technologies considered are grid-to-vehicle (G2V) and vehicle-to-grid (V2G) technologies, as well as advanced metering infrastructure.

The results reveal that in the BLUE Map SG_{MIN}, case peak load will increase until 2050 by 28% in OECD EUR, 15% in OECD NA, 25% in OECD PAC and by 200% in China while demand increases by 23%, 25%, 32% and 152%. Assuming the same demand growth, the BLUE SG_{MAX} case shows that smart grids can substantially offset the increases in peak load the different regions to 13%, 1%, 12% and 176%. These finding indicate that smart grids can considerably lower peak load and therefore optimise the asset utilisation. Asset modernisation can therefore compensate extension projects to meet future demand needs.

Introduction

Smart grids are a key suite of technologies to deal with pressing current and future needs in the electricity sector and to enable the effective adoption of low-carbon energy technologies such as variable renewable energies and electric vehicles.

The IEA has identified five smart grid-specific drivers in the electricity sector:

- demand increase
- penetration of electric vehicles (EVs) and plug-in hybrid vehicles (PHEVs)
- deployment of variable renewable energy sources
- peak load increase
- ageing infrastructure

The first three drivers have been examined in the *Energy Technology Perspectives 2010* (*ETP 2010*) Baseline and BLUE Map Scenarios (IEA, 2010a), but these scenarios have not taken into consideration the impacts of smart grid technologies on the electricity system infrastructure.

Box 1 Energy Technology Perspectives (ETP) scenario descriptions

The ETP BLUE Map Scenario assumes that global energy-related carbon dioxide (CO_2) emissions are reduced to half their current levels by 2050. This scenario examines ways in which the introduction of existing and new low-carbon technologies might achieve this at least cost, while also bringing energy security benefits in terms of reduced dependence on oil and gas, and health benefits as air pollutant emissions are reduced. The BLUE Map Scenario is consistent with a long-term global rise in temperature of 2˚C to 3˚C, but only if the reduction in energy-related CO_2 emissions is combined with deep cuts in other greenhouse-gas (GHG) emissions. The Baseline Scenario considers the business-as-usual case, not reducing emission levels to any predetermined goal by 2050. The BLUE Map and Baseline Scenarios are based on the same macroeconomic assumptions.

According to results from *ETP 2010*, worldwide electricity demand increases by 151% in the Baseline Scenario and 117% in the BLUE Map Scenario between 2007 and 2050. The demand increase is not equally spread across regions and therefore requirements for grid modernisation and extension will vary between areas with low and high growth. OECD member countries exhibit low growth in demand, ranging from 30% to 37%, but have expansive and ageing networks where the modernisation and expansion is constrained by highly complex regulatory regimes. Non-OECD countries or regions such as China, India and Africa, and the Middle East show greater growth, ranging from 104% to 509%. The priority in these regions is more focused on building up a new electricity system infrastructure, which is already being undertaken in some regions.

Continued investment is required in all electricity systems in order to maintain reliability and power quality, but the regional differences must be taken into account. In developing countries and emerging economies, the needs to reduce commercial and technical losses and to increase rural electrification are often of greater importance in addition to the high growth rates in demand. In other regions large-scale deployment of variable renewable energies (wind, concentrated solar power and solar photovoltaics) is occurring in order to reduce the dependence on fossil fuels and reduce carbon emissions. System operators are confronted with increasing difficulties of balancing supply and demand as variable generation assets increase uncertainty and complexity of operation. Smart grid technologies enable higher penetration rates of variable renewable energy sources (VRE) by increasing system flexibility through advanced generation and demand-side management. Further, improved management and monitoring through smart grids can maximise the utilisation of the existing infrastructure and address existing issues within power systems.

In addition to the changes in electricity generation, the *ETP 2010* BLUE Map Scenario estimated that the share of electricity used by the transportation sector will increase to 11% of overall demand by 2050, while it is marginal today. This includes all modes of transport, but the major reason for this increased electrification is the adoption of electric and plug-in hybrid electric vehicles (EVs and PHEVs). This additional demand must be managed in a strategic fashion by smart grids to minimise the impact on peak load. Over the long term, smart grids also enable electric vehicles to act as energy storage devices and support the grid operation. The use of electricity for heating and cooling is also expected to increase with the deployment of new technologies such as heat pumps.

This report analyses the impact of the changes described in *ETP 2010* on the electricity system, and the role of smart grids. As a first step, peak demand will be modelled in the context of the *ETP 2010* Baseline and BLUE Map Scenarios. In this case, the impact of variable renewable energies will not be considered, but will be examined in subsequent analyses. This working paper analyses the evolution of peak load in four key regions: OECD Europe, OECD North America, OCED Pacific and China.

Annual peak load is defined in this paper as the maximum load of the system that occurs within a one-year period. The load on the electricity system changes over the course of the day and through the year according to electricity consumption. Peak load has been considered for this analysis because the generation and network capacity are dimensioned to meet the maximum load requirement, plus reserves, during a year. Peak load is increasing at a faster rate than average demand, resulting in increased infrastructure investment in comparison to the amount of electricity being consumed on an annual basis. The increased use of electric devices (such as EVs/PHEVs) could intensify load-curve peaking.

Smart grids can be a key enabler of technologies to shift, to store or to shape electricity demand according to the available capacity of production, transmission and distribution assets. Thus, they can provide solutions to reduce existing and future peak demand levels. This analysis will explore the potential benefits of smart grids in varied regional contexts.

Box 2 Characteristics of smart grids

The world's electricity systems face a number of challenges, including ageing infrastructure, continued growth in demand, the integration of increasing numbers of variable renewable energy sources and electric vehicles, and the need to improve the security of supply and reduce CO2 emissions. Smart grid technologies offer ways not just to meet these challenges, but to do so in a more affordable and more sustainable manner.

Smart grids characteristically

- enable informed participation by customers
- accommodate all generation and storage options (including VRE)
- enable new products, services and markets (including DR, EVs)
- provide the power quality for the range of needs
- optimise asset utilisation and operating efficiency
- provide resiliency to disturbances, attacks and natural disasters

Source: IEA, 2011.

The *IEA Smart Grid Technology Roadmap*,[1] released in April 2011, provides a complete description of smart grid technology and policy. The roadmap stresses the need for more regional analysis of electricity systems. There is no one-size-fits-all solution to address the challenges in the electricity sector, and priorities differ among regions. Other related IEA efforts have estimated the prospects for large-scale storage in decarbonised power grids (IEA, 2009b) and modelled load shifting using electric vehicles in a smart grid environment (IEA, 2010b). This working paper presents the methodology chosen to model the annual peak load development to 2050 in the *IEA Smart Grid Technology Roadmap*.

Section 2 introduces the scope of the problem. A reference case for peak load is developed in Section 3, and several smart grid deployment cases and the impact on peak load in section 4. Section 5 summarises the main results from the analysis, while section 6 draws some conclusions.

[1]The *IEA Smart Grids Technology Roadmap* is available at: www.iea.org/papers/2011/smartgrids_roadmap.pdf.

Scope of the Analysis

Peak load as a system design metric

The evolution of peak load can be considered an important system design metric for grid operators and planners. The scope of this study is limited to peak load, but in preparation for future work, other drivers will be partially discussed.

Overall electricity demand and the daily schedules of electricity usage are currently major influences on peak load. In the future, peak load will be influenced by new or increased demands such as the penetration of clean energy technologies, such as electric vehicles and plug-in hybrid electric vehicles (EVs/PHEVs) and the increased use of electricity for heating and cooling through technologies such as heat pumps. A high penetration of EVs/PHEVs will affect the peak load significantly if the charging is not controlled. In fact many EV/PHEV users might charge their EVs/PHEVs simultaneously in the early evening when peak system demand already exists, and further stress the grid capacity. Scheduled charging, however, can shift some load from the evening to the early morning and thus flatten the load curve. In a more advanced deployment stage, EVs/PHEVs could provide so-called vehicle-to-grid (V2G) services and could be used as electric storage to reduce peak generation capacity by discharging electricity from the battery to the grid.

Smart grid technology, through the use of advanced monitoring and control equipment, could reduce peak demand and thus prolong and optimise use of the existing infrastructure. Investments in generation, transmission and distribution might be deferred through the adoption of smart grids, and smart grid investment might be partially facilitated by using synergies between grid renewal and modernisation.

Scenario planning for smart grid deployment

Scenario planning is a method of making decisions under high uncertainty by developing plausible future scenarios (Schoemaker, 1995). In the preparation of this study and the IEA *Technology Roadmap: Smart Grids*, scenario planning was adopted to develop deployment scenarios for smart grids. The following simplified scenario-planning method was used to develop a reference case and several analysis cases, although many variations exist:

1. Set the scope and time horizon of the analysis.
2. Decide on drivers for the change and define various assumptions.
3. Identify scenarios based on the reference cases.
4. Develop quantitative models.

In the following, the process to develop the smart grid deployment cases is explained step by step. Brainstorming plays an essential role in all the above steps except the last.

First, the scope and time horizon of the analysis are fixed in order to develop the framework of the analysis. The analysis focuses on a deployment case for smart grids in four regions: the three regions formed by member countries of the OECD (OECD Europe, OECD North America and OECD Pacific) and China. Table 1 presents the composition of the analysed regions, which is consistent with previous IEA studies. The time horizon, *i.e.* the period of the analysis – 2010 to 2050 – was adapted to *ETP 2010*.

Table 1 Composition of analysed regions

Region	Country
China	China
OECD EUR	Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, UK
OECD NA	Canada, Mexico and United States
OECD PAC	Australia, Japan, Korea, New Zealand

In the second step, the drivers for change in the electricity system are set and various assumptions are elaborated. Five drivers are defined: demand increase, peak demand increase, increased use of VRE, integration of EVs/PHEVs, and ageing infrastructure. These drivers are interlinked but require different actions. Peak load is chosen as a key metric since it is not heavily analysed in the *ETP 2010* scenarios and is strongly linked to the other four drivers.

Simplifications are made and deployment cases are developed based on a single reference case. The reference case for demand increases, peak demand and integration of EVs/PHEVs in all four regions is derived from *ETP 2010* Baseline and BLUE Map Scenarios. The reference case shows the basic trends without smart grid technologies and is presented in detail in the section "Estimation of regional peak load for the Baseline and BLUE Map Scenarios."

A quantitative model is developed by focusing on peak load as a metric for grid operation and analysing the interrelated drivers described above. Although the methodology of system dynamics is widely used in order to analyse the dynamical behaviour of the system (Ford, 1997), the IEA developed the simpler static model as a first-cut analysis. The quantitative model is presented in detail in the section "Quantification of smart grid cases (SG_0, SG_{MIN}, SG_{MAX})."

Development of Peak Load Reference Case

This section presents the peak load reference case for each of the four regions analysed, based on the Baseline and BLUE Map Scenarios. The reference case is intended to be used to demonstrate the evolution of the electricity system that does not consider smart grid deployment. The reference case for each region will then be used in the following section to examine the change in peak load due to several smart grids cases up to 2050.

Peak load estimation approach

A basic concept of the analysis is that the annual peak load in a country or region tends to be correlated with its annual generation demand. Annual peak load *PL* (GW) is defined here as the maximum load of the system that occurs within a period of one year. It should be noted that the annual peak load represents the highest load value which is marked at one point within a year and is not a function of time as opposed to power load in daily load curves. Electric power systems, which comprise generation plants, transmission and distribution networks, are designed on the basis of their ability to sustain the peak load and contingency reserves.

In this working paper, annual average load L_{AVE} is defined as the average electric power load in a country or region over a one-year period. It can be obtained by dividing the annual generation demand D_{GEN} by the total hours of a year, *i.e.* 8 760 hours:

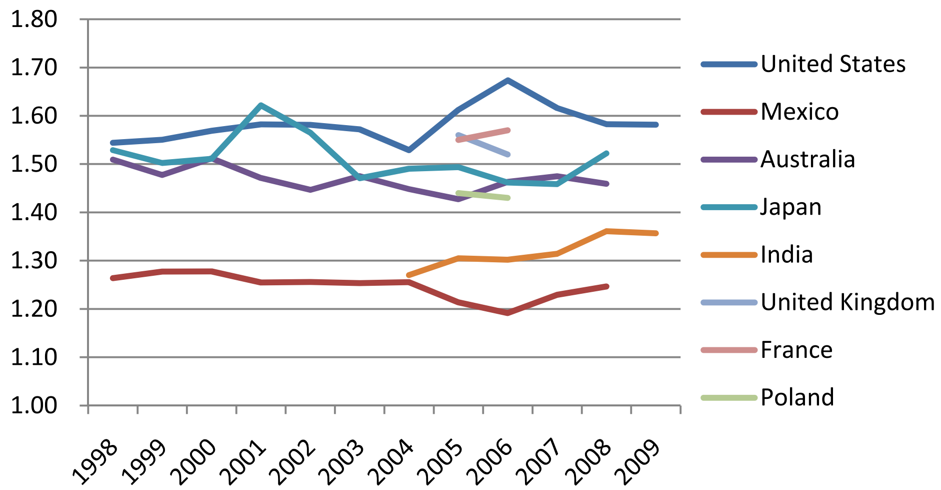
$$L_{AVE}(GW) = \frac{D_{GEN}(TWh)}{1000 \cdot y(8760h)}$$

The peak coefficient C_{PL} is defined as a ratio[2] of annual peak load to annual average load and is an indication for the flatness of the load curve.

$$C_{PL} = \frac{PL}{L_{AVE}}$$

Historical peak coefficients calculated from historical statistical data of annual peak load and annual average load in several countries show a constant trend (Figure 1).

Figure 1 Peak coefficient in different countries, 1998-2009



[2] This coefficient is correlated with the utilisation factor used in power system planning. UF = 1 / C_{PL}.

Figure 1 shows C_{PL} ranging from 1.2 to 1.7. These values are coherent with utilisation factors measured by power systems operator, from 59%[3] in power systems peaking with air conditioning to 86% in power system peaking with air conditioning and with a large industrial base-load. It is noteworthy that this figure does not reflect some winter peaking power systems, for example in Canada (i.e. Quebec, Manitoba, New-Brunswick) and Norway, where high penetration of electric baseboard heating causes a C_{PL} factor of 2 (utilisation factor of assets of only 50%).

Sector changes in future demand are expected to alter the peak coefficients of regions. In general, residential and service sector demand fluctuates more over the course of the day and between seasons than industrial sector demand. Secondly, contractual arrangements with industrial sectors are often put in place to curtail their demand in circumstances where the grid needs to reduce peak demand. Therefore, a growing fraction of residential and service demand is expected to increase the peak coefficient, as the intraday demand profile amplifies its peak behaviour. This approach considers such pattern changes in sector demand.

Estimation procedure

For each region:

1. The peak coefficient between annual peak load and annual average load from historical data is determined.
2. The peak coefficient is extrapolated by considering future sector demand changes in the *ETP 2010* Baseline and BLUE Map Scenarios.
3. The annual average load is determined from the generation demand projections of the *ETP 2010* Baseline and BLUE Map Scenarios.
4. The peak load reference case is derived up to 2050 by multiplying the regional peak coefficient and annual average load projection.

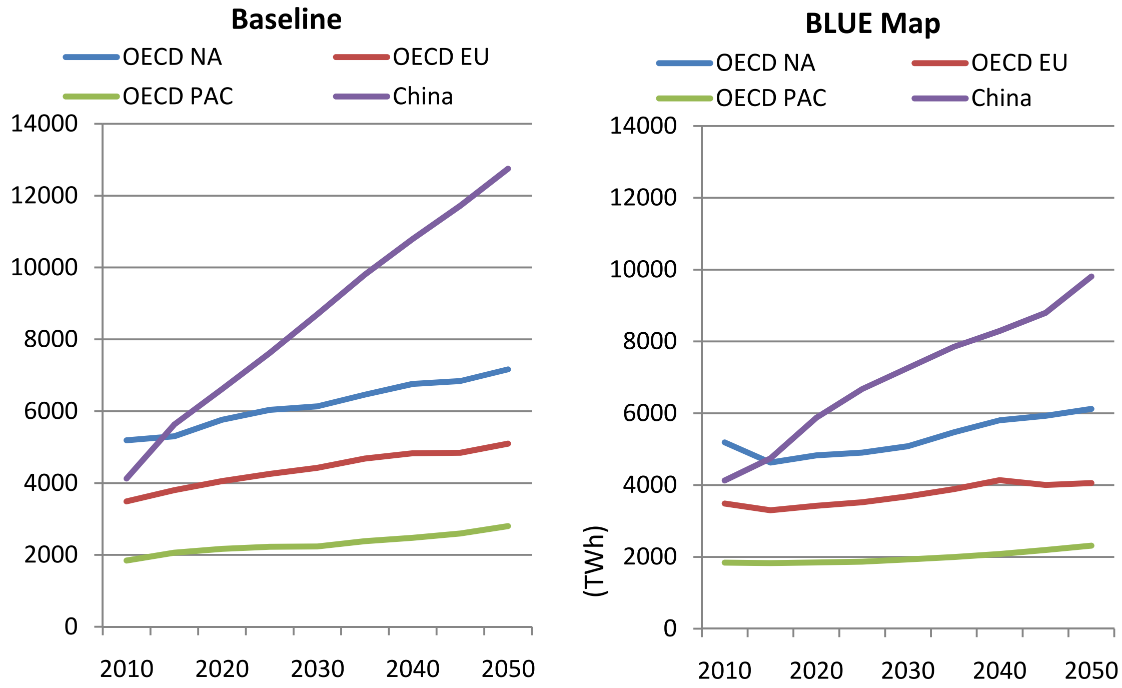
Baseline and BLUE Map Scenarios for demand to 2050

Electricity generation data from *ETP 2010* Baseline and BLUE Map Scenarios have been used for estimating peak load. Worldwide electricity demand is expected to more than double by 2050. In the Baseline Scenario, there is a broadly commensurate increase in electricity demand across all sectors. Electricity demand in the BLUE Map Scenario is 13% lower than in the Baseline Scenario owing to increased efficiency in the end-use sectors. Some of the increased efficiency in industry and buildings is, however, offset by higher demand for electricity for additional uses, such as heat pumps and EVs/PHEVs. The ETP2010 figures for the year 2010 are calibrated in this study with the World Energy Outlook 2010 Current Policy Scenario (IEA, 2010c).

The impact of EV demand is treated separately in the section "Quantification of Smart Grid Cases (SG_0, SG_{MIN}, SG_{MAX})," and EV demand is subtracted from future generation demand in the development of this reference case for both Baseline and BLUE Map Scenarios in order to avoid double counting. Figure 2 presents the regional generation demand excluding EV generation for the Baseline and BLUE Map Scenarios.

[3] 1/1.7 = 0.59 or 59% | 1/1.2 = 0.83 or 83%.

Figure 2 Generation demand, excluding EV generation demand, for the Baseline and BLUE Map Scenarios



Estimation of regional peak load for the Baseline and BLUE Map Case

Correlation between historical annual peak load and generation demand

Peak load coefficients are established from historical data sources for the four regions analysed: OECD NA,[4] OECD EUR,[5] OECD PAC[6] and China.[7] For the analytical approach of the paper, it is assumed that the peak loads within every analysed region coincide despite a geographical span though different time zones and climates. Future projections and historical profiles of annual peak load and generation demand are considered at the supply side. Transmission and distribution losses are included in those historical values and are consequently higher than the demand-side values.

For OECD NA and OECD PAC, data covering a ten-year period are used to obtain the historical peak load coefficient for the regions. As data are only available up to 2008, peak load coefficients for years 2009 and 2010 are estimated as average values over the latest 10 years. For OECD NA, data are only available from 1987 to 1996 and are used for Canada. For OECD EUR, the total peak and demand up to 2010 is available. For China, historical peak load data are not available. The peak coefficient is considered as an average of OECD Pacific and India.[8] Thus, the following presents how the various variables were gathered.

- Total peak load (GW) = sum of annual peak load of all countries in a region
- Total demand (TWh) = sum of annual generation of all countries in a region

[4] Source: EIA statistics for US, IEA statistics for Mexico and Canada data.

[5] Source: Eurelectric 2008 Power Statistics.

[6] Source: IEA Statistics.

[7] Source: IEA Statistics for historical generation demand, no data available for historical peak load.

[8] Source: IEA statistics of historical generation demand, 17th Electric Power Survey of India for peak load.

- Annual average load (GW) = Total demand (TWh) ÷ 1 000 ÷ 8 760 (h)
- Peak coefficient = total peak load ÷ annual average load

Table 2 OECD EUR

	1980	1990	2000	2005	2006	2010
Total peak (GW)	333	432	505	530	473	605
Total demand (TWh)	1 915	2 526	3 131	3 218	2 897	3 728
Average load (GW)	219	288	357	367	331	426
Peak load coefficient	1.53	1.50	1.41	1.44	1.43	1.42

Table 3 OECD NA

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Total peak (GW)	756	785	781	805	804	805	864	906	882	858
Total demand (TWh)	4 307	4 452	4 403	4 522	4 551	4 657	4 773	4 797	4 908	4 888
Average load (GW)	492	508	503	516	520	532	545	548	560	558
Peak load coefficient	1.54	1.55	1.55	1.56	1.55	1.51	1.59	1.65	1.57	1.54

*(year): For Canada, only data from 1987 to 1996 were available.

Table 4 OECD PAC

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Total peak (GW)	244	253	266	266	256	268	276	279	287	288
Total demand (TWh)	1 434	1 512	1 525	1 571	1 572	1 636	1 685	1 708	1 761	1 738
Average load (GW)	164	173	174	179	179	187	192	195	201	198
Peak load coefficient	1.49	1.47	1.53	1.48	1.42	1.43	1.43	1.43	1.43	1.45

Table 5 China

	2009	2010
Peak load coefficient	1.41	1.41

Consideration of sector changes in future demand

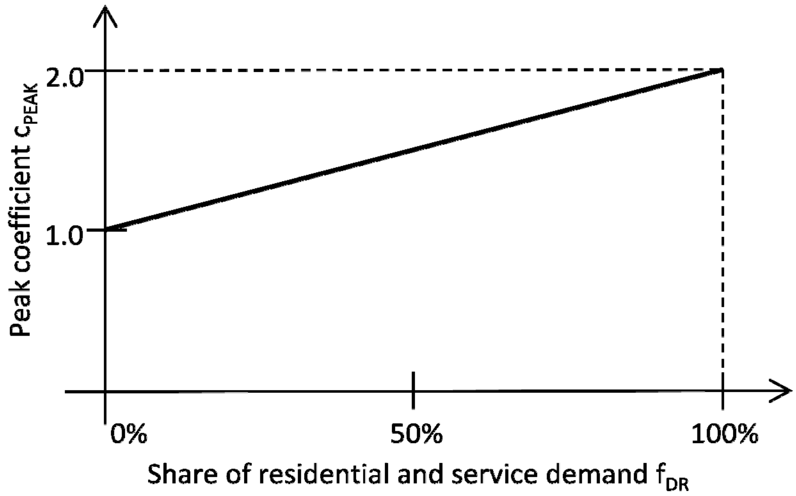
In order to quantify influence of sector demand changes on peak coefficient, this paper makes the following assumptions:[9]

1. Peak coefficient of residential and service sector demand is 2.0.
2. Peak coefficient of industry, transformation and others sector demand is 1.0.
3. The impact of transportation is modelled separately in the smart grid scenarios section.

[9] These assumptions were developed by comparing peak coefficients of Japan and Australia in Figure 1 and 2007 shares of the residential and service demand in Figure 4.

Figure 3 illustrates the influence of the composition of the end-use sector on the peak coefficient. The peak coefficient is determined by the percentage share of residential and service sector demand. Accordingly, the assumptions indicate that a 10% increase in the share of residential and service demand in a region will bring about an increase of 0.1 in peak coefficient; conversely, a decrease of 10% will cause a decrease of 0.1.

Figure 3 Peak coefficient in function of share of residential and service demand



Regional sector demand changes are obtained from *ETP 2010*. In OECD PAC, the residential and service sector accounted for 57% of total generation demand in 2007. It is increasing in the Baseline Scenario to 59% by 2030 and decreasing to 55% by 2050, whereas in the BLUE Map Scenario it is decreasing to 56% by 2030 and further to 44% by 2050 (Figure 4). Such changes in sector demand contribute to reduce the peak coefficient in the BLUE Map Scenario, indicating that demand profiles will peak less. On the contrary, in the Baseline Scenario the peak coefficient does not show considerable change and the peak load behaviour of the demand patterns will not significantly improve (Figure 5). Similar comparisons were made for OECD NA, OECD EUR and China.

Figure 4 OECD PAC generation demand by sector

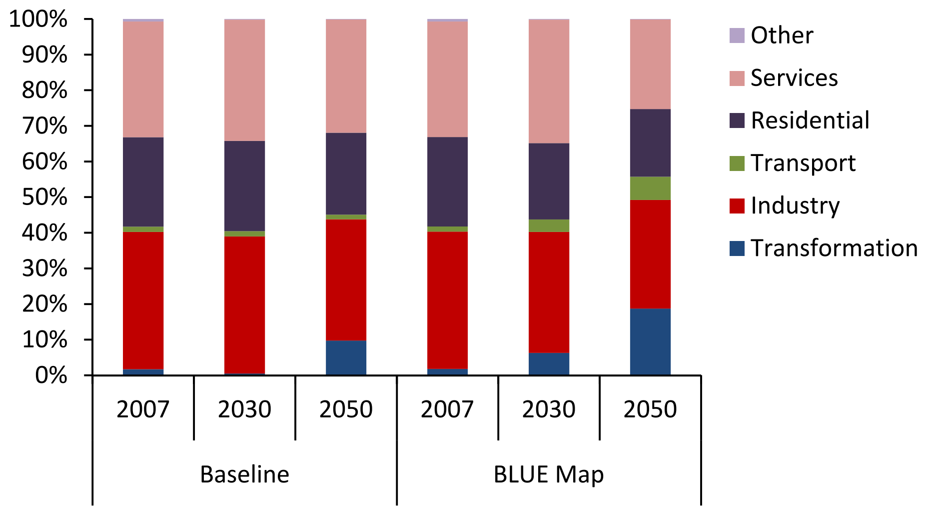
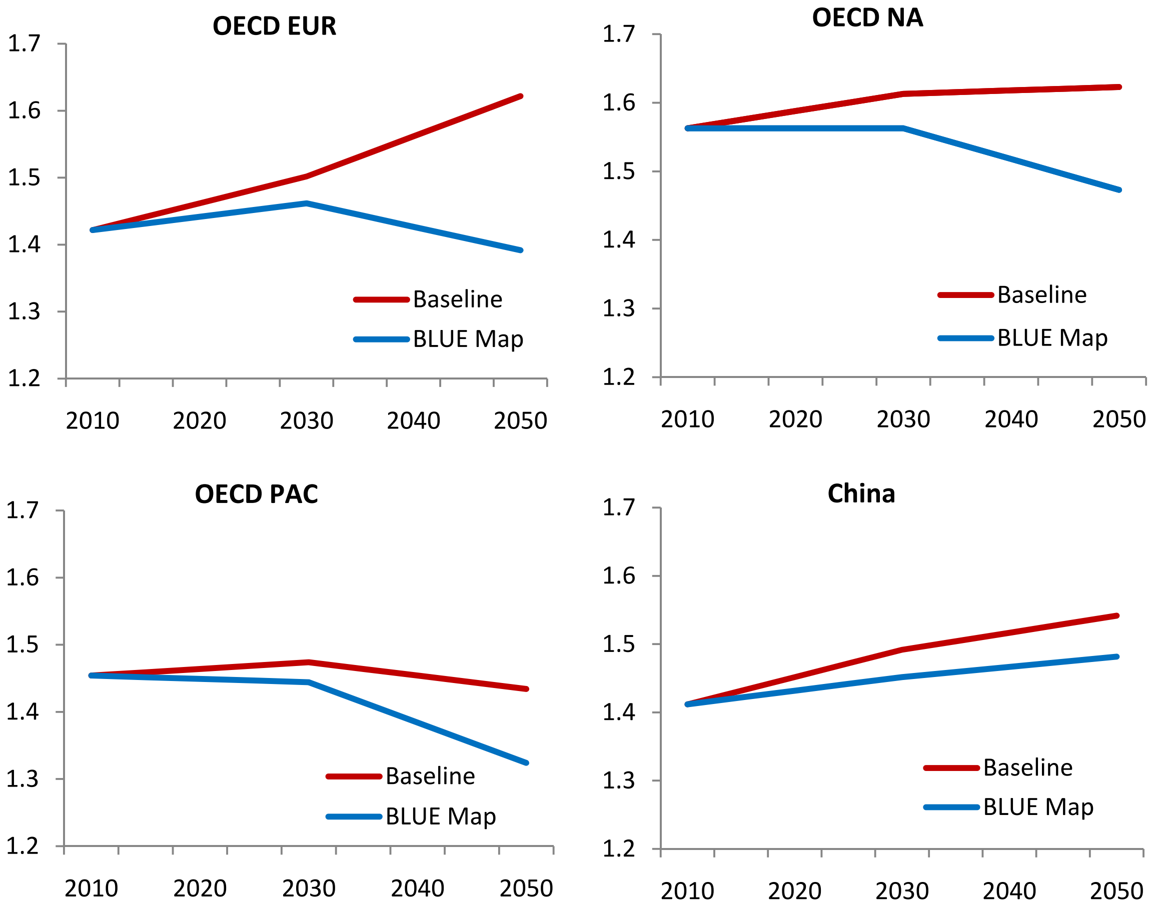


Figure 5 Peak coefficients with sector demand changes considered

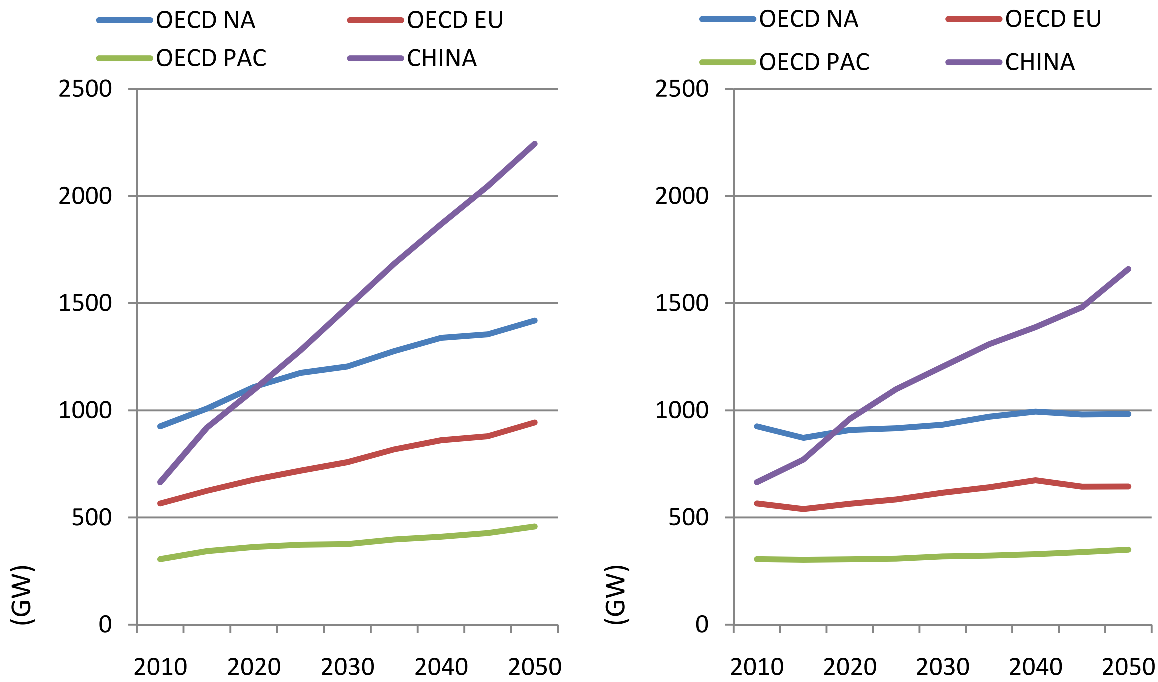


Regional reference case peak load estimation

Annual average load of each region was calculated from generation demand projections of *ETP 2010* for the Baseline and BLUE Map Scenarios (Figure 2). Each region's peak load to 2050 was estimated on a yearly basis by multiplying the peak coefficient of each region with the annual average load. In other words, peak load curves in Figure 6 were determined by using the average load obtained from Figure 2 and the peak coefficients of Figure 5.[10] In the BLUE Map Scenario, peak load increases at a slower rate than in the Baseline Scenario, since the changing pattern of sector demand will gradually reduce the peak coefficient.

[10] It should be again noted that the contribution of EVs/PHEVs have not been considered in these peak load estimates, as EV/PHEV demand has been excluded from generation demand projections.

Figure 6 Peak load reference estimates for the Baseline and BLUE Map Scenarios



Quantification of Smart Grid Cases (SG_0, SG_{MIN}, SG_{MAX})

Modelling approach (cases and system boundaries)

The reference case that has been outlined in the previous section does not consider the impacts of smart grid technology deployment. Future scenarios must especially take into account the technological evolutions in the electricity sector and adapt the reference case accordingly. This section presents the modelling approach used to develop the smart grid cases.

The objective is to illustrate the evolution of peak load between 2010 and 2050 and to model the interactions of the different demand-side drivers on peak load in order to demonstrate the need for, and potential of, smart grid technologies. The rationale for this approach is as follows:

- Peak demand determines the operational capacity of infrastructure at the generation, transmission and distribution levels, both technically and financially. Operation of the network must always balance generation and demand within the capacity of the overall network. For a system operator and planner, peak load is consequently a critical design metric.
- Peak demand analysis assesses optimisation potentials for system operation.
- The IEA's Grid Integration of Variable Renewables[11] project could be considered in future work to quantify the impacts of smart grids on variable generation deployment.

In order to develop simplified but realistic and meaningful scenarios, this analysis builds based on two main uncertainties: technology and policy. The *ETP 2010* Baseline and BLUE Map Scenarios forecast two potential paths for major technology evolutions until 2050. The Baseline Scenario assumes that no new energy and climate policies are introduced. The BLUE Map Scenario uses existing and new low-carbon technologies to cut CO_2 emissions by half their current levels by 2050 and at least cost. The *ETP* scenarios include socioeconomic factors such as population and wealth growth. Smart grids are considered to be a key enabler to achieve the targets defined by the BLUE Map Scenario, but are not considered in the *ETP 2010* analysis.

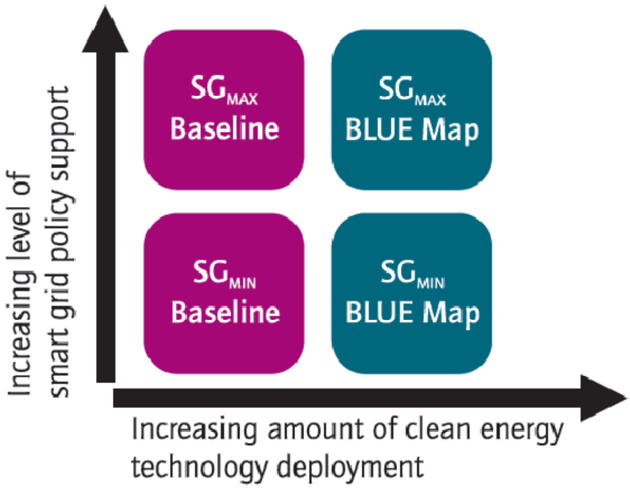
In order to incentivise the introduction of smart grid technologies, policies must be developed to support both smart grid technology development and to revise the current regulation and market organisation needed for smart grid deployment. It is in this context that the quantification of smart grid cases is carried out.

A scenario without any smart grid support and no smart grid deployed, SG_0, is considered as a reference case to fully demonstrate the need for smart grids in the electricity system. The smartening of the grid is an evolving process and not a one-time event (IEA, 2011); the question is not whether it will happen, but when and to which extent. Two policy support scenarios have been developed to adopt smart grids: at a minimum level, SG_{MIN}, and at a maximum level, SG_{MAX}.

By combining all variations from these uncertainties, four scenarios can be derived (Figure 7).

[11] The IEA GIVAR project aims to establish a flexibility assessment method for variable renewable energy sources; see *Harnessing Variable Renewables - A Guide to the Balancing Challenge*, May 2011.

Figure 7 Smart grid deployment cases matrix



Source: IEA, 2011.

Model description and parameter assumptions

The goal of the modelling is to capture the main driving forces and interactions within the electricity system in order to quantify the impact on peak load PL (GW) of both clean energy and smart grid technologies and of policy support. In this analysis, the modelling is governed by three main drivers:

- Generation demand
- Number of EVs/PHEVs
- Demand response enabled by smart grid deployment

The parameters in this mathematical description are estimated using empirical values and are presented in the following paragraphs. All the coefficients are assumed to be identical throughout the regions of interest if not stated otherwise.

AMI penetration rate

The automated metering infrastructure (AMI) describes in this paper the capability of the system to actively manage the demand side. The AMI penetration (%) represents the share of end-users connected to the electricity grid through smart meters. This equipment enables dynamic pricing of electricity by measuring the consumption in hourly or smaller intervals. This device could also communicate with in-home display within the customer premises and display real-time consumption and price of the electricity. Smart meters without dynamic electricity rates, however, provide no incentive to manage peak. This study assumes that dynamic pricing will be adopted following the installation of smart meters and AMI.

In order to evaluate the potential impact on peak demand, the share of smart meters installed is introduced as an auxiliary variable to measure the deployment of AMI.

Aggressive smart meter adoption programmes are being launched throughout all analysed regions. The implementation of smart meters can be assumed to follow the shape of a logistic curve with exponential growth initially, followed by a slowing growth and finally reaching maturity as most households are equipped with smart meters. Thus, deployment of AMI can be represented by the following equations:

$$\frac{dAMI}{dt} = \mathrm{r} * \mathrm{STEP}\left(\mathrm{T_{DR}} - \mathrm{T_{Lag}}\right) * AMI(t) * (1 - AMI(t))$$

The coefficient r is the growth rate. The step function STEP is assumed to trigger at a fixed time interval (T_{Lag}) before the moment at which demand response (T_{DR}) is in operation, with T_{Lag} assumed to be five years. The STEP function in the above discussion is defined as:

$$STEP = \begin{cases} 0 \; if \; T_{DR} - T_{Lag} < 0 \\ 1 \; if \; T_{DR} - T_{Lag} > 0 \end{cases}$$

Most governments of the regions analysed have recently launched smart meter deployment programmes (Table 6).

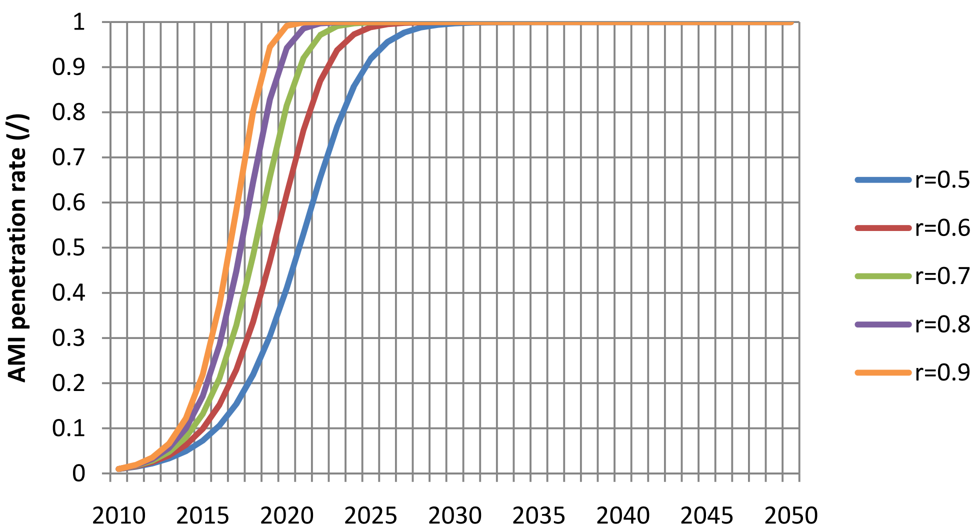
Table 6 Overview of smart meter rollout plans

Regions	Countries	Smart meter projections
OECD EUR	Italy[A]	100% today
	Finland[B]	80% by 2014
	United Kingdom[C]	100% by 2019
	France[D]	95% by 2016
	Ireland[E]	100% by 2017
	European Union[F]	80% by 2020
OECD NA	United States[G]	40 million≈33% by 2015
	Canada[H,I]	Ontario: 100% by 2010 British Columbia: 100% by 2012
OECD PAC	Australia[J]	100% by 2015
	Japan	100% by 2020
	Korea[K]	100% by 2020
China		100% by 2020/2025

Note: If no source is given, the numbers are unofficial announcements.

Sources: (A) ENEL (n.d.); (B) Ministry of Trade and Industry, Finland, 2009; (C) Department of Energy and Climate Change, UK, 2011; (D) Ministry of Ecology and Energy, France, 2010; (E) Commission for Energy Regulation, Ireland, 2011; (F) European Commission, 2009; (G) Ernst & Young (n.d.); (H) Ministry of Energy, Ontario (n.d.); (I) BC Hydro, 2011; (J) Budde, 2010; (K) MKE, 2010.

Figure 8 AMI penetration in function of growth rate



Note: r is the growth rate of the logistic curve.

According to Table 6, smart meters should be installed universally in most countries in the first half of the 2020s. Accordingly, a growth rate r of 0.7 was chosen from Figure 8.

Generation demand

Generation demand (D_{GEN} = (TWh)) indicates electricity consumption as estimated by the *ETP 2010* projections. These *ETP 2010* scenarios consider energy-efficiency improvements that are therefore not influenced by smart grids deployed in this model. Demand response programmes are not expected to reduce demand but simply to shift consumption from peak to off peak time. Smart grids can reduce generation demand by reducing T&D losses though advanced control and monitoring tools. Hence the ETP numbers are adjusted by an efficiency coefficient α as follows:

$$D_{GEN} = \alpha(t, AMI) * D_{GEN}^{ETP}(t)$$

This paper assumes that all regions will reduce T&D losses to today's best practice value L_{BEST} if smart grid technologies are successfully implemented along the value chain. According to the IEA energy balances, grid losses represent 7% of generation demand in OECD EUR, OECD NA and China, but only 5% in OECD PAC. OECD PAC is therefore used as L_{BEST}. As the remaining losses are mainly due to physical losses in the conductive material, the potential of smart grids to reduce those losses is limited. All analysed regions have announced ambitious T&D modernisation plans; the first loss reductions are expected as early as 2015. The loss reductions can only be achieved if the necessary equipment has been installed. These loss reductions are an on-going process that is modelled by using the AMI penetration rate where the shares of AMI are used as a metric for smart grid penetration in general:

$$\alpha(t, AMI) = 1 - \left(L_{ETP}^{2010} - L_{BEST}^{2010}\right) * \mathrm{AMI(t)}$$

$$with\ L_{BEST}^{2010} = L_{OECD\ PAC}^{2010} = 5\%$$

Table 7 Loss coefficients

Coefficient	Value
L_{BEST}	0.05 (OECD PAC)
L_{ETP}	0.07 (rest of OECD and China)

EV/PHEV considerations

EVs/PHEVs are powered by an electric battery that must be charged from the grid, referred to as grid-to-vehicle (G2V). If connected during peak hours and if the access to the grid is not managed in an appropriate manner, EVs/PHEVs will increase peak load. EVs/PHEVs however also have the potential to act as grid storage devices and feed electricity back into the grid at peak hours. This function is referred to as vehicle-to-grid (V2G) and relies on a smart grid that enables greater participation of demand side for balancing, peak reduction of contingency actions.[12] Hence, the actual potential of storage available from EVs/PHEVs in this model depends on smart grid implementation, which is in turn determined by the share of EVs/PHEVs in combination with advanced meters (AMI) and time-of-use pricing.

The number of EVs/PHEVs ($N_{EV/PHEV}$=(#)) determines the total stress on the grid resulting from all individual vehicle load. It is assumed that no other factor will interact with the number of EVs/PHEVs deployed and that the *ETP 2010* scenarios for EVs/PHEVs are not influenced by smart

[12] Other storage options are not considered in this analysis at this time.

grid policy support. *ETP 2010* projections show EVs/PHEV deployment in the BLUE Map Scenario only and not in the Baseline Scenario. These ambitious projections expect around 100 million EVs and PHEVs to be sold per year in 2050 and can only be enabled by adopting smart grids.

The actual load of a battery connected to the grid while charging or discharging is discussed in the following paragraphs.

Charging power

A normal household plug has between 1.8 kW in Northern America (110 V at 16 A) and 3.7 kW (230 V at 16 A) in Europe. Many existing battery vehicle chargers use the National Electrical Code (NEC) “Level 2” standard of 6.6 kW. The first automotive power electronics unit designed for G2V (in production by AC Propulsion) provides 80 A in either direction. Thus, by Joule’s law (Power (W) = potential difference (V) * electric current (I)), it provides 19.2 kW at a residence (240 V) or 16.6 kW at a commercial building (208 V) (Kempton, 2005). In addition, industrial chargers (or so-called fast-charging stations) have capacities of 43 kW (Circontrol, 2010) to 200 kW (ABB, 2010). The French utility EDF uses the following categorisation levels for chargers: 3 kW, 6 kW, 24 kW, 43 kW, 150 kW (Legrand, 2009). The US Department of Energy uses three classification levels: 1.44 kW, 3.3 kW and 60 kW to 150 kW (DOE, 2008). The last level is for fast-charging.

Fast charging can reduce battery life and it is not assumed to become the preferred charging mode. The best fast-charging mode will potentially be battery swapping, where the discharged battery is replaced within a few minutes by a fully charged one. The battery-swapping station would rather use slow charging to optimise battery life.

France expects that 90% of vehicles will be charged using slow charging and 10% using quick charging (RWTH, 2010). By using this distribution and assuming 3.7 kW for slow charging and 40 kW for fast, an average charging load P_{CHG} of 7.3 kW is assumed.

Discharging power

The charging power is governed by the charger, which determines the load of the charging process on the grid (G2V). If a vehicle provides V2G services to the grid, it is uncertain whether the discharging power is limited by the charger or the battery. It should be noted that this paper only considers V2G services that provide energy from the battery and not from the engine of a PHEV (which can be operated as a generator).

The power that a vehicle can deliver can be approximated with the following formula (Kempton, 2005):

$$P_{VEH} = \frac{\left(E_S - \eta_{EV/PHEV} * (d_D + d_{RB})\right) * \eta_{INV}}{t_{DISP}}$$

where P_{VEH} is maximum power from V2G (kW); E_S the stored energy available as direct current (kWh) to the inverter; d_D the distance driven (km) since battery was full; d_{RB} the distance (km) of the range buffer required by the driver; η_{VEH} the vehicle electric driving efficiency (kWh/km); η_{INV} the electrical conversion efficiency of the direct to alternating current inverter (dimensionless); and t_{DISP} is the time the vehicle's stored energy is dispatched (hours).

The IEA’s *EV/PHEV Technology Roadmap* assumes that EVs will have a battery storage capacity E_S of about 30 kWh while PHEVs will have approximately 8 kWh. It also assumes an average efficiency η_{VEH} of 0.15 kWh/km to 0.2 kWh/km, with some additional reserve battery capacity (IEA, 2009a).

The distance driven since the battery was full, d_D, depends on various characteristics: the driving pattern, the vehicle type, and the driver's strategies for being prepared to provide power. The average daily vehicle distance travelled per driver in the United States is 51.2 km. Kempton (2005) assumes that half the average daily vehicle distance has been travelled when the driver parks the vehicle and plugs it to the grid, thus D_D=26 km. The distance of the range buffer d_{RB} is the minimum remaining range required by the driver as a reserve. The range buffer is determined by the V2G service company or the driver, and does not depend on the vehicle characteristics. A study with Californian drivers found that 32 km was sufficient for most drivers (Kurani, Turrentine and Sperling, 1994). This paper uses a range buffer d_{RB} of 32 km for EVs. PHEVs can be fully discharged, as they can always be operated with the combustion engine powered by fuel. Thus d_{RB} is set to 0 for PHEVs. An inverter efficiency η_{INV} of 0.93 is assumed.

The electricity market determines how long the vehicle can be dispatched. The time dispatched (t_{DISP}) can be a few minutes for spinning reserves up to several hours for peak power.

Table 8 presents the calculations of the available power from the battery by using the equation presented above.

Table 8 Discharging power of the vehicle battery

	EV	PHEV	EV	PHEV	EV	PHEV	EV	PHEV
t_{DISP} (h)	1	1	2	2	3	3	4	4
D_D (km)	25.6	25.6	25.6	25.6	25.6	25.6	25.6	25.6
d_{RB} (km)	32	0	32	0	32	0	32	0
E_S (kWh)	30	8	30	8	30	8	30	8
H_{INV} (/)	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
$\eta_{EV/PHEV}$ (kWh/km)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
P_{VEH} (kW)	17.18	2.67	8.59	1.33	5.72	0.89	4.29	0.66
$P_{EV/PHEV}$ (kW)	9.93		4.96		3.31		2.48	

According to IEA data, the number of EVs and PHEVs is projected to be similar, so the power of battery vehicles $P_{EV/PHEV}$ (EVs and PHEVs) can be calculated by averaging the power for EVs and the power of PHEVs. Peaking hours occur between 3 and 5 hours per day. A battery capacity for a t_{disp} between 3 and 4 hours is therefore chosen, and for simplification a discharging load (P_{DISCHG}) of 3 kW is assumed.

The discharging load (P_{DISCHG}) of the battery is lower than the power of the charging station (P_{CHG}), and as a result is the limiting factor for discharging.

The share of vehicles connected to the grid during peak load (f_{EV}) will strongly influence the load of the total vehicle fleet on the grid. In the United States, vehicles are parked 96% of the time. The fraction of vehicles connected during peak hours is expected to be lower, since vehicle use is also higher during peak hours. This paper assumes that 50% of the vehicles are connected and charge from the grid during peak hours. The smart grid, however, can actively control the load by partially disconnecting some vehicles and thus throttle peak demand. Managed charging is expected to penetrate the market soon, as it is a low-cost and mature technology that is available today. It only requires a communication device in the charger that transmits relevant battery information to the grid operator who, by remote control, can partially disconnect a certain number of charging vehicles if the grid capacity is saturated. Passenger car electrification is underway and the additional load must be managed to a certain degree.

V2G is a less confirmed concept, because it is more cost-intensive and it requires building up considerably more infrastructure to enable bidirectional flow. The battery management for grid support might be different than for vehicle propulsion and thus degrade the battery. The degradation should be included in the price compensation from the utility to the customer, but might be difficult to monetise. Moreover, consumer acceptance can be expected to be much greater for G2V than for V2G, as it may be easier to accept uncommitted charging than reducing driving range by discharging to the grid. Finally, electric car and battery warranty issues with the car manufacturer may not support V2G. The market potential of V2G is limited compared to G2V.

The tariff structure will strongly influence the timing of charging/discharging. This paper expects, therefore, that the fraction of EVs connected during peak load will be smaller. The share of vehicles connected to the grid, $f_{EV\ G2V}$, is set to 50% in the SG_0 Scenario. An effective pricing policy discourages peak charging (G2V), but encourages peak discharging to support the grid (V2G). Hence, $f_{EV\ G2V}$ decreases through effective smart grid policy support. It is assumed that uncommitted and managed charging in an optimised electricity grid can disconnect an additional 40% and 60% of the EVs connected during peak time in the SG_{MIN} and SG_{MAX} cases respectively, compared to SG_0. The fraction of vehicles connected, $f_{EV\ V2G}$, increases as the smart grid policy scenario becomes more supportive: the share of vehicles available is 5% in the SG_{MIN} and 15% in the SG_{MAX} cases. This may be conservative compared to a study from Turton and Moura (2008), which expects vehicles to be available for V2G electricity services for 50% of the time.

Table 9 Fraction of vehicles connected during peak load f_{EV}

f_{EV}	G2V	V2G
SG_0	50%	0%
SG_{MIN}	30%	5%
SG_{MAX}	20%	15%

EV/PHEV equations

The impact on peak load of EVs/PHEVs connected to the grid can therefore be modelled as follows:

$$PL_{G2V/V2G} = \underbrace{\delta(t) * N_{EV/PHEV}(t)}_{G2V} - \underbrace{\varepsilon(t) * N_{EV/PHEV}(t) * AMI(t)}_{V2G}$$

where the coefficient δ depends on the fraction of vehicles connected to the grid for charging during peak load f_{EV} ($0 < f_{EV} < 1$) and on the load of one vehicle that is being charged P_{CHG}. ε depends on the fraction of EVs connected, f_{EV}, and the average discharging power P_{DISCHG}.

For the entire vehicle fleet and over time, an average value for f_{EV} and P_{CHG} is assumed:

$$\delta = f_{EV}(SG_{0/MIN/MAX}) * P_{CHG}$$

EVs connected to the grid can serve as storage devices and reduce peak demand from the grid by providing electricity from the battery. For the entire vehicle fleet and over time, this paper assumes an average value for f_{EV} and P_{DISCHG}:

$$\varepsilon = f_{EV}(SG_{0/MIN/MAX}) * P_{DISCHG} * STEP(T_{DR})$$

As most of the smart grid functionalities are only feasible if DR is available, T_{DR} is defined as the year DR capabilities are enabled.

Demand-response considerations

Demand-response (DR) programmes can, in time, shift the electricity use of customers from peak to off peak periods to support grid operation by reducing peak load. DR is assumed to have the same potential in the residential and service sector to partially reduce peak loads.

The coefficient ϑ is defined by the fraction of residential and service demand to all demand sectors f_{DR} (as derived from *ETP 2010*), by the potential of demand-response r_{DR} and the share of AMI:

$$\vartheta = f_{DR} * r_{DR} * \mathrm{AMI} * \mathrm{STEP}(\mathrm{T_{DR}})$$

The fraction of residential and service demand to all demand sectors f_{DR} was derived from *ETP 2010*. Values from the year 2030 were chosen for the whole time interval between 2010 and 2050. The analysed regions present very diverse sector energy uses; thus, it was necessary to make a regional differentiation.

Table 10 Fraction of residential and service demand to all demand sectors f_{DR}

f_{DR} (2030)	Baseline	BLUE Map
OECD EUR	59%	55%
OECD NA	59%	70%
OECD PAC	59%	56%
China	27%	23%

The potential of DR is estimated to be between 5% and 22.9% depending on the technology and policies (Faruqui *et al.*, 2007). For the scope of this study, the minimal and maximal potentials of r_{DR} were set to 5% and 15% respectively. It was assumed that there is no interrelation between DR and G2V/V2G. Hence the impact of DR on peak load can be described by the following equation

$$PL_{DR} = \underbrace{\vartheta(t) * PL^{ref}(t)}_{\substack{DR\ in\ residential \\ and\ service\ sector}}$$

Resultant peak load equation

The peak load reference case presented in the section "Development of Peak Load Reference Case" is an extrapolation of peak load using no smart grid technologies. Future technologies are expected to influence electricity consumption behaviour and will affect peak load accordingly. EVs/PHEVs and demand response (DR) are two key areas that are included in the modelling of the peak load scenarios.

Peak load can be modelled using the following equation:

$$PL(t) = PL^{ref}(t) + \underbrace{\delta(t) * N_{EV/PHEV}(t)}_{G2V} - \underbrace{\varepsilon(t) * N_{EV/PHEV}(t) * AMI(t)}_{V2G} - \underbrace{\vartheta(t) * PL^{ref}(t)}_{\substack{DR\ in\ residential \\ and\ service\ sector}}$$

Overview of smart grid cases

With a fully defined set of equations and coefficients, the cases can be quantified (Table 11). It should be highlighted that there are no EVs in the Baseline Scenario and that consequently neither the effect of V2G nor that of G2V is considered in the Baseline Scenario.

Table 11 Summary of the modelled smart grid scenarios

	SG_0	SG_{MIN}	SG_{MAX}
Baseline	/	$DR_{resid/serv}$ low	$DR_{resid/serv}$ high
BLUE Map	G2V unmanaged	$DR_{resid/serv}$ low G2V managed low V2G low	$DR_{resid/serv}$ high G2V managed high V2G high

Discussion of Results

In this section, the potential of smart grid technology is evaluated with the peak load estimations up to 2050 for all regions. In addition, key smart grid drivers are compared qualitatively across all regions.[13]

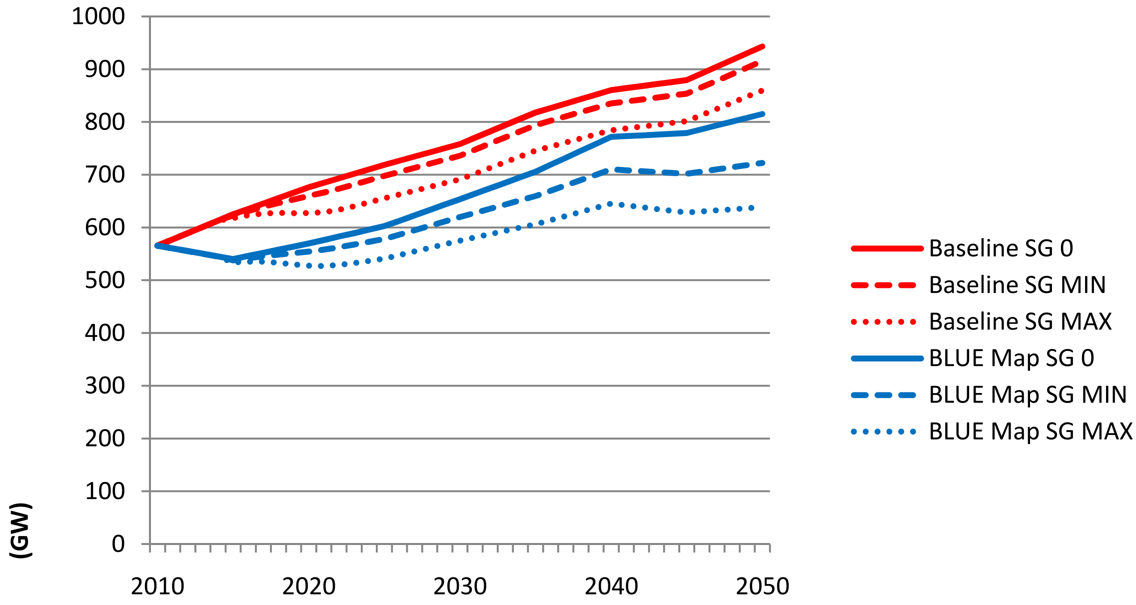
Overview of peak load evolution in the analysed regions

OECD Europe

The growing share of VRE is a key challenge for grid integration in Europe. In Europe, electricity demand grows until 2050 by 46% in the Base $SG_{0,}$ and by 23% in the BLUE Map SG_{MAX} case. The peak load increase has been estimated at between 67% and 13% respectively for those cases. The increased energy use in the residential and service sectors makes demand response in those sectors much more effective in OECD Europe compared to China. Many European governments aim to have smart meters installed in every household by 2020 to enable efficient demand side management.

The BLUE Map SG_0 case illustrates that the deployment of EVs/PHEVs significantly increases peak load, whereas in the BLUE Map SG_{MAX} case, the need for additional capacity can be shifted until 2025 by employing both DR and using stored electricity in EVs/PHEVs to reduce peak load. The capital investments saved by not expanding the grid could be used to upgrade the existing grid with smart grid technologies. In the BLUE Map SG_{MAX} case, peak demand can be reduced by 12% compared to the BLUE Map SG_{MIN} case.

Figure 9 Estimated peak load evolution in OECD EUR, 2010-2050



[13] The ETP2010 figures for the year 2010 are calibrated with the World Energy Outlook 2010 Current Policy Scenario (IEA, 2010c) in this study and therefore the slightly differ from the results presented in the IEA Smart Grids Technology Roadmap (IEA, 2011).

OECD North America

OECD NA is currently the largest electricity market in the world. The peak-load scenario in OECD NA generally has the same characteristics as in Europe. It is a low-growth region with an ageing grid that needs to be modernised to guarantee resilient operation. Focussing on the transmission network in the United States, a smart grid approach could enhance operation through transmission system monitoring and management. The potential of shifting the need for additional capacity in time is promising, and the current grid can handle peak load capacity until 2050 if a smart grid is fully deployed. This is demonstrated in the BLUE Map SG_{MAX} case in which the peak load increases only 1% by 2050, even as the overall demand for electricity increases by 25%. In comparison with the SG_0 case, this is the perfect opportunity to reinvest savings in the deployment of smart grid technologies. Many efforts are therefore expected to incorporate demand-side management to increase system flexibility and avoid capacity expansion.

Figure 10 Estimated peak load evolution in OECD NA, 2010-2050

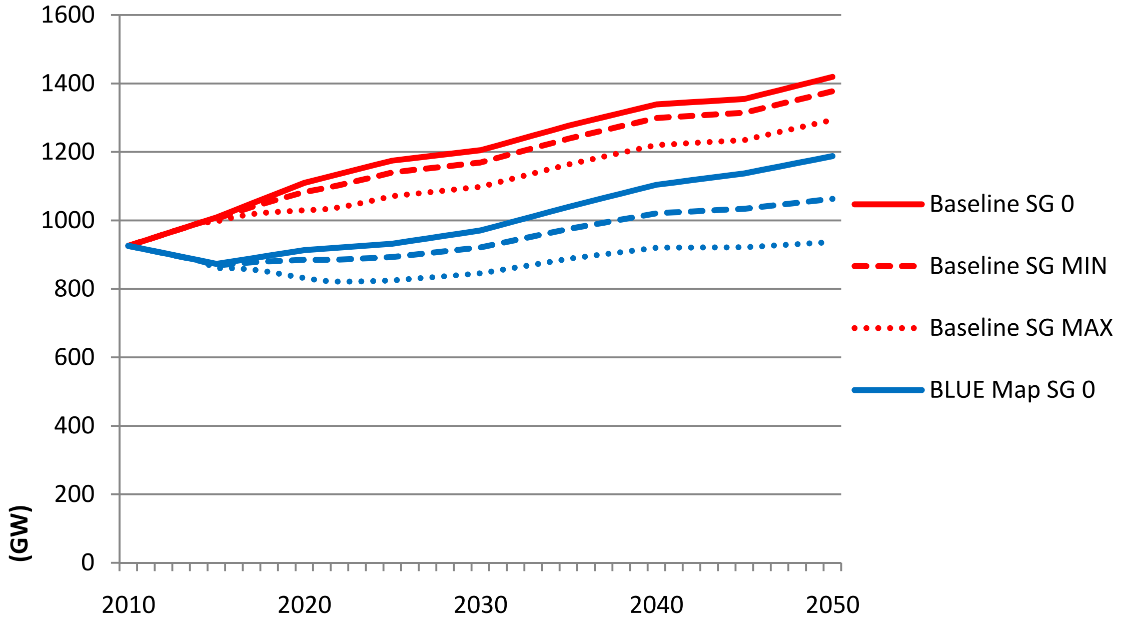
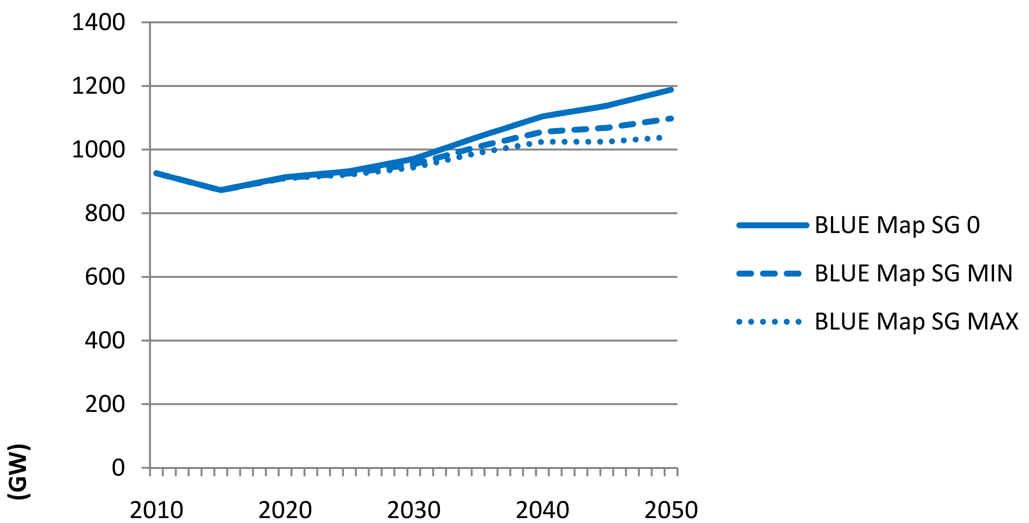


Figure 11 Estimated peak load evolution in OECD NA without using demand response, 2010-2050

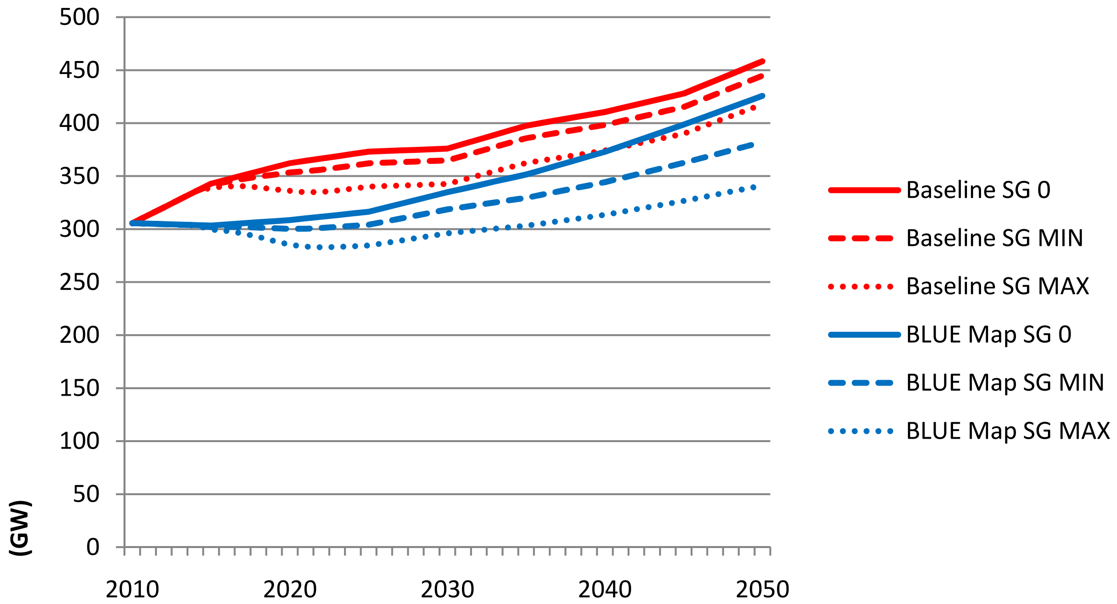


To highlight the effect of electricity storage from EVs/PHEVs, V2G and G2V services alone (without demand-response capabilities) are also analysed for OECD NA. Figure 11 shows that in the BLUE Map SG_0 case, total peak load increases by 29% over the 2010 value by 2050. When G2V and V2G services are applied, peak load increase is reduced to 19% and 12% in BLUE Map SG_{MIN} and BLUE Map SG_{MAX} respectively. All four analysed regions show similar trends.

OECD Pacific

OECD Pacific is a low-growth region for electricity. Until 2050, demand is expected to increase by 52% in the Base SG_0 and 32% in the BLUE Map SG_{MAX} case. In addition, peak load will rise by 50% in the Base SG_0 and 11% in the BLUE Map SG_{MAX} case. Smart grids can potentially reduce peak load in 2050 by 11% in the BLUE SG_{MAX} case compared to the BLUE SG_{MIN} case. The modelling of OECD Pacific requires special consideration: although modelled as a single region, the various countries of OECD Pacific are not highly interconnected. The potential for interregional T&D systems is limited because the region is geographically fragmented. Further analysis must be carried out to determine how this will impact the areas of concern demonstrated in the model. Opportunities to interconnect with contiguous non-OECD countries should also be considered.

Figure 12 Estimated peak load evolution in OECD PAC, 2010-2050

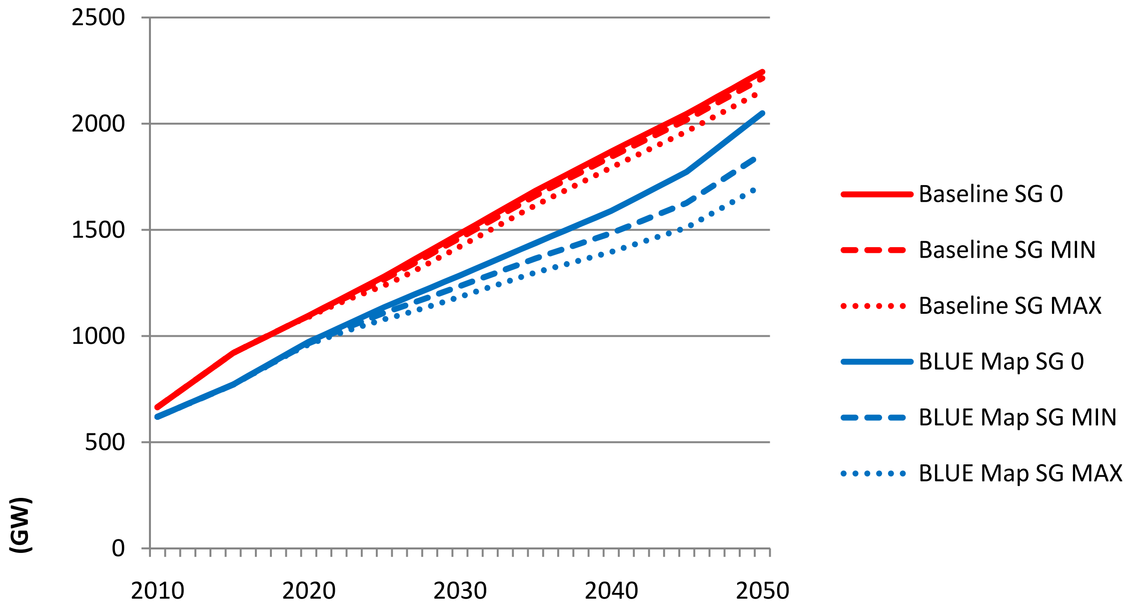


China

China is expected to be the largest electricity market in the world in 2050. The high demand growth (152% in the BLUE Map Scenario to 209% in the Baseline Scenario) from 2010 to 2050 in China results in high peak load growth in all scenarios. To meet the significant growth in peak load (Figure 13) until 2050, the current grid must be expanded and huge infrastructure investments will be needed along the whole electricity value chain (*i.e.* generation, transmission, distribution and end-use). A long-term strategic smart grid plan would allow China to leapfrog towards a smart grid that operates efficiently and integrates new clean-energy technologies to minimise the financial and environmental burdens.

In both the SG_{MIN} and SG_{MAX} in the Baseline and BLUE Map cases the effect of demand response is modest, as the residential and service sector portions of total energy end-use (f_{DR}) is low. The industrial sector is by far the dominant sector. China could further investigate the load curve profiles of its industries, categorise them and determine subsectors that present peak behaviour, and develop a specific demand-response programme for those industries. In the BLUE Map SG_{MAX} case, peak load can be lowered by 8% compared to the BLUE Map SG_{MIN} case. This reflects potentially large capital savings in the grid-infrastructure investments needed to support growth. Considering that the impact of DR is low, this number essentially highlights the potential of EVs/PHEVs in supporting grid operation. China is pushing for the introduction of EVs and is leading in technology development. China is a key market, expected to have more than 100 million EVs and PHEVs on the roads in 2050.

Figure 13 Estimated peak load evolution in China, 2010-2050



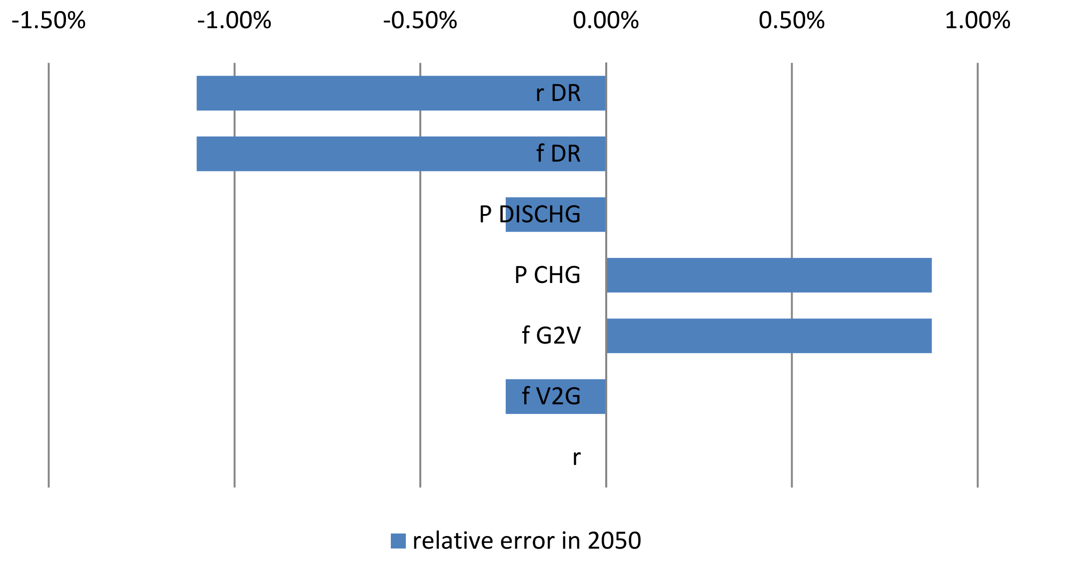
Sensitivity analysis

A sensitivity analysis was carried out in order to recognise uncertainty in the parameters considered. The impact on peak load is analysed by increasing every parameter individually by 10% and reiterating the calculations. The relative error in peak load between the initial and increased value is compared for every parameter in order to detect how sensitive the results are to the assumed parameters. The following parameters were analysed:

- maximal DR potential (r_{DR})
- fraction of residential and service sectors compared to all sectors (f_{DR})
- discharging capacity (P_{DISCHG})
- charging capacity (P_{CHG})
- fraction of vehicles connected G2V and V2G (f_{G2V} , f_{V2G})
- AMI growth rate (r)

The results are presented for OECD NA BLUE Map SG_{MAX} in Figure 14. The relative error is in the range of 0.3% to 1.1%, except for the AMI growth rate where the relative error is 0%. The growth rate determines the saturation speed of the logistic curve, but does not influence the saturation level, which is achieved by 2050 for both the initial and increased growth-rate values. A sensitivity analysis between 2011 and 2050 has indicated that the highest relative error of the growth rate is 1.4% in 2019. The chosen parameters are relatively insensitive to + 10% fluctuations.

Figure 14 Sensitivity analysis for OECD NA BLUE Map SG_{MAX} case



Qualitative comparison of smart grid driver metrics between regions

Peak load and the three smart grid drivers discussed in *ETP 2010* (demand, VRE and EVs) are compared qualitatively in order to derive priorities and differences for smart grid deployment in each region. The goal of the deployment scenario presented in the *Smart Grids Technology Roadmap* is to identify key priorities, action items and milestones in technology and policy to a broad range of stakeholders, including policy makers, regulators, equipment manufacturers, utilities and grid operators.

The results from the modelling devised in this paper and *ETP 2010* are displayed graphically to illustrate the differing system needs of the four regions. Different colours were assigned to low, medium, high and very high levels for the drivers (Table 12) to demonstrate the different impacts on the various regional electricity systems from 2010 to 2050 in each scenario. This approach aims to show where regional focus is needed to achieve a considerable reduction in CO_2 emissions; the analysis is therefore limited to the BLUE SG_{MIN} and SG_{MAX} cases.

The following smart grid driver metrics were modelled in this study:

- **Increase in demand:** Compared with 2010 levels (TWh).
- **Peak load increase:** Compared with 2010 levels (GW). This includes all contributions to peak load increases, such as EV/PHEV deployment and higher electricity use in buildings.

The following drivers derive directly from *ETP 2010* analysis and therefore show no difference between the SG_{min} and SG_{max} Scenarios:

- **VRE deployment:** Portion of overall demand produced by variable renewable resources to total generating capacity.
- **EV/PHEV portion of peak demand:** Portion of peak demand as a result of EV/PHEV deployment.

Table 12 Smart grid driver metrics for graphical representation (%)

	Low	Medium	High	Very High
Increase in demand	0 <x ≤ 50	50 <x ≤ 100	100<x ≤ 150	150 < x
Peak load increase	0 <x ≤ 5	5 <x ≤ 20	20 <x ≤ 35	35 < x
VRE deployment	5 <x ≤ 10	10 <x ≤ 20	20 <x ≤ 35	35 < x
EV/PHEV portion of peak demand	1 <x ≤ 5	5 <x ≤ 10	10 <x≤ 15	15 < x

This approach is not meant to indicate definitively that any one driver is indispensible for reliable and secure operation of the grid; rather it provides a relative comparison between regions to show where focus could initially be placed to address longer-term concerns. For example, the impact of EVs/PHEVs in China and Europe is very similar, but since China's grid and demand are much larger than Europe's by 2050, the number of vehicles deployed for the same impact is twice as high. Although there is a significant difference in the scale of deployment relative to the respective system sizes, both regions could place the same emphasis on this area for smart grid deployment.

Figure 15 compares all key smart grid drivers qualitatively for all four regions in the BLUE SG_{MIN} and BLUE SG_{MAX} Scenarios. The deployment of smart grids will allow for construction of electricity infrastructure that can be better planned and designed to meet the needs of today and the future while reducing the negative impacts on peak demand with the deployment of EVs/PHEVs.

BLUE SG_{MIN} and BLUE SG_{MAX} cases

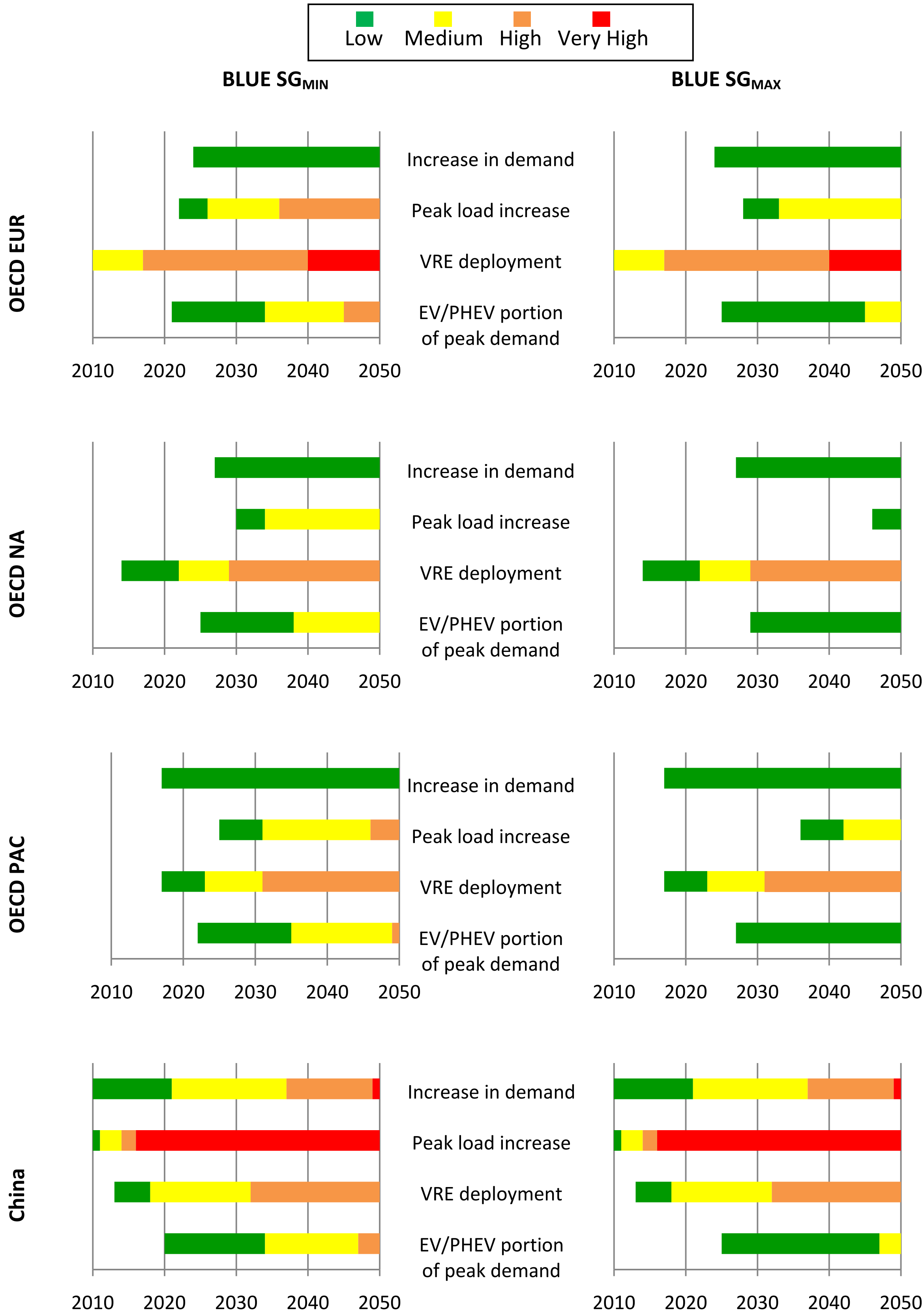
In the BLUE SG_{MIN} case, clean-energy technologies are deployed significantly, although policy support for smart grids is modest. OECD countries demonstrate similar trends with respect to all drivers (Figure 15), but OECD Europe must address all drivers earlier. OECD NA can, and indeed must, benefit significantly from the deployment of smart grids, given that it is the largest electricity market in the world at this time and has an ageing infrastructure, especially at the transmission system level. In this respect, focussing largely on the demand-response benefits of smart grids and transmission system monitoring and management could be highly valuable. OECD Pacific, although modelled as a single region, comprises countries that are not highly interconnected. Further analysis must therefore be carried out to determine how this fragmentation will impact the areas of concern demonstrated in the model. Furthermore, the OECD PAC grid is the newest grid among the three OECD regions and modernisation might be less urgent from an electricity-reliability perspective.

A high demand growth, dominated by economic growth, requires capacity expansions in China. EV/PHEV integration is an important concept that must be prepared, but that will not have a considerable impact on the grid before 2030 at the earliest, when the number of vehicles becomes significant. It is essential, however, that the infrastructure to assure G2V and V2G be in place by then.

In the BLUE Map SG_{MAX} case, clean-energy technologies are deployed significantly and are strongly supported by smart grid policies. This strong policy support is reflected in the high use of demand response in the residential and service sector, controlled EV/PHEV charging and increased use of V2G services. The BLUE Map SG_{MAX} Scenario can only be achieved by considerable consumer engagement: the regulator must develop a pricing scheme that incentivises the adoption of smart grid services. A particular challenge is to internalise external benefits such as environmental protection and energy efficiency into a tariff structure guaranteeing affordable access to electricity.

Smart grid technologies reduce peak load, which determines the capacity of the T&D infrastructure. Thus, they may make it possible to delay capacity expansions and their concomitant financial investments. The peak-load bar in Figure 15 illustrates how a smart grid can defer grid expansions in OECD countries between the BLUE SG_{MIN} and BLUE SG_{MAX} Scenarios, if the necessary modernisations are performed to enable smart grids.

Figure 15 Smart grid drivers in the BLUE SGMIN and BLUE SGMAX cases across all analysed regions compared to 2011



Conclusions

Recognising the difficulty of developing a unique smart grid deployment indicator by scenario planning, this paper has analysed the smart grid drivers in the context of peak load. The first step of the methodology was to determine smart grid drivers. Generation demand, peak load, the share of VRE, transport electrification and the age of the grid are all increasing and pressing for the adoption of smart grid technologies that manage the grid in an efficient and resilient way. With this prospect in mind, smart grid deployment is expected to be an economical and environmental solution to meet the goals set in the *ETP 2010* BLUE Map Scenario concerning demand, VRE and EV/PHEV adoption. Helping to support an ageing infrastructure was considered but not included at this stage in the quantitative analysis because of missing data.

The modelling estimated peak load evolution between 2010 and 2050 for OECD EUR, OECD NA, OECD PAC and China with the deployment of smart grids at a minimal (SG_{MIN}) or maximal (SG_{MAX}) level. The analysis is focused on the demand side, in particular demand response in the service and residential sector, as well as the integration of EVs/PHEVs. EVs/PHEVs connected to the grid during peak time further stress the grid, but the impact can be diminished through controlled charging, which would automatically disconnect select vehicles, according to objective criteria transparently applied. In the longer term, EVs/PHEVs will provide V2G services by supplying electricity stored in the battery to the grid and lowering peak load. The potential of V2G is limited, as it is technologically more complex and expensive. As has been mentioned, the introduction of AMI and smart meters alone has no or a limited impact on peak demand, but should be accompanied by the adoption of dynamic pricing to provide the appropriate price signals to the customer.

The results reveal that, depending on the region, smart grids can lower peak load considerably, by 8% to 12% in 2050 in the BLUE Map SG_{MAX} case compared to that of the BLUE Map SG_{MIN}. OECD countries are low-growth regions with more or less ageing grids. The deployment of a smart grid could considerably postpone investments in grid expansion and use saved funds to leverage smart grid investments. OECD EUR is strongly deploying VRE and plans to achieve a share of 37% in terms of capacity in the BLUE Map Scenario by 2050. A first priority for smart grid deployment could be the implementation of an advanced grid management system. Smart grid technologies could enable OECD NA in the BLUE SG_{MAX} case to keep peak load at today's levels until 2050 to delay grid expansions. China's strong demand growth leads to high peak load increases in all cases. The grid will need to be enlarged dramatically, providing the opportunity for the country to build up a modern, efficient and resilient grid. EVs/PHEVs have been characterised as a double-edged sword that could both stress and support the grid during peak load, depending on the deployment level of a smart grid.

The methodology presented has demonstrated its ability to develop a smart grid deployment scenario that quantifies the impact of smart grids and compares different regions. Further refinements will include the modelling of supply-side flexibility and a detailed analysis of the impact of clean-energy technologies (such as distributed and embedded renewable energy generation) on the load curve. It would also be valuable to discuss electricity storage more generally, including other technologies (*e.g.* grid batteries, hydro storage and compressed air).

Acronyms and abbreviations

AMI	advanced metering infrastructure
CO_2	carbon dioxide
C_{PL}	peak coefficient
d_D	distance driven since battery was full (km)
D_{GEN}	annual generation demand (TWh)
DR	demand response
d_{RB}	distance of the range buffer required by the driver (km)
EIA	Energy Information Administration
E_S	stored energy available as direct current to the inverter (kWh)
ETP 2010	Energy Technology Perspectives, 2010 (IEA publication)
EUR	Europe (countries part of the analysed region are listed in Table 1)
EV	electric vehicles
f_{DR}	fraction of residential and service demand to all demand sectors (%)
f_{EV}	share of vehicles connected to the grid during peak load (%)
IEA	International Energy Agency
L	T&D losses (%)
L_{AVE}	annual average load (GW)
NA	North America (countries part of the analysed region are listed in Table 1)
$N_{EV/PHEV}$	number of EVs and PHEVs
OECD	Organisation for Economic Co-operation and Development
PAC	Pacific (countries part of the analysed region are listed in Table 1)
P_{CHG}	charging power (kW)
P_{DISCHG}	discharging power (kW)
PHEV	plug-in hybrid electric vehicles
PL	peak load (GW)
P_{VEH}	maximum power from V2G (kW)
r	growth rate
r_{DR}	reduction potential of demand response (%)
SG	smart grid
STEP	step function
T&D	transmission and distribution
t_{DISP}	moment a vehicle's stored energy is dispatched (hours)
T_{DR}	time at which demand response is in operation
VRE	variable renewable energy sources
η_{INV}	electrical conversion efficiency of the direct to alternating current inverter (%)
η_{VEH}	vehicle electric driving efficiency (kWh/km)

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