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THESIS

"Next generation smart electricity networks and price-directed demand in competitive electricity markets"

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ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΙΑΣ

ΤΜΗΜΑ ΜΗΧΑΝΙΚΩΝ ΗΛΕΚΤΡΩΝΙΚΩΝ ΥΠΟΛΟΓΙΣΤΩΝ,
ΤΗΛΕΠΙΚΟΙΝΩΝΙΩΝ ΚΑΙ ΔΙΚΤΥΩΝ

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

«Έξυπνα δίκτυα ηλεκτρικής ενέργειας επόμενης γενιάς και ζήτηση κατευθυνόμενη από την τιμή σε ανταγωνιστικές αγορές ηλεκτρικής ενέργειας»

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Ευχαριστίες

Θα ήθελα να ευχαριστήσω θερμά τον επιβλέπων καθηγητή μου κύριο Ελευθέριο Τσουκαλά για την εμπιστοσύνη του και την καθοδήγησή του κατά την εκπόνηση της διπλωματικής μου εργασίας.

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Στην οικογένεια μου,

Στην Ειρήνη

ΠΕΡΙΛΗΨΗ

Στην διπλωματική αυτή εργασία παρουσιάζονται τα βασικά οικονομικά και οι τεχνολογίες που είναι απαραίτητες για τη δημιουργία μιας ανταγωνιστικής αγοράς ηλεκτρικής ενέργειας (pool-based, short-term, competitive electricity market coordinated by a system operator).

Ο στόχος της ανταγωνιστικής αγοράς ηλεκτρικής ενέργειας είναι η ισορροπία μεταξύ προσφοράς και ζήτησης ενέργειας, ειδικά σε περιόδους αιχμής, σε ένα κόσμο που οι απαιτήσεις για ηλεκτρική ενέργεια αυξάνονται συνεχώς. Η συνεχής παροχή ηλεκτρικής ενέργειας είναι ζωτικής σημασίας για τη ζωή των ανθρώπων. Οι διακοπές στην ηλεκτρική ενέργεια λόγω της μη δυνατότητας του συστήματος να παρέχει ενέργεια σε περιόδους αιχμής, εμπεριέχει τεράστιο κόστος τόσο οικονομικό όσο και κοινωνικό.

Στην ανταγωνιστική αγορά ηλεκτρικής ενέργειας η συμμετοχή του καταναλωτή στον καθορισμό της τιμής της ενέργειας είναι αυτό που την κάνει να ξεχωρίζει. Ο καταναλωτής δεν είναι ποια αυτός που δέχεται την τιμή της ενέργειας αλλά αυτός που την καθορίζει. Ο καταναλωτής επιλέγει σε τι τιμή είναι πρόθυμος να αγοράσει ηλεκτρική ενέργεια και οι παραγωγοί ανταγωνίζονται μεταξύ τους για να εξυπηρετήσουν τη ζήτηση. Η όλη διαδικασία συντονίζεται από ένα διαχειριστή συστήματος (system operator). Ο διαχειριστής συστήματος δέχεται προσφορές (market biddings) από τους παραγωγούς και τους καταναλωτές και σε στιγμιαίο χρόνο υπολογίζει την τιμή ισορροπίας της αγοράς, έτσι ώστε η προσφορά να ισούται με τη ζήτηση. Η διαδικασία των προσφορών λαμβάνει χώρα στις αγορές άμεσης παράδοσης (spot markets) και για ένα μικρό χρονικό διάστημα, ας πούμε κάθε 15 λεπτά, καθορίζεται η νέα τιμή ισορροπίας της ηλεκτρικής ενέργειας.

Επίσης στην ανταγωνιστική αγορά ηλεκτρικής ενέργειας εισάγεται η έννοια των συμβολαίων μακράς διάρκειας ώστε να αντισταθμίζεται ο κίνδυνος της συνεχούς αλλαγής των τιμών της ηλεκτρικής ενέργειας αλλά και του κόστους συμφόρησης μεταφοράς της ηλεκτρικής ενέργειας πάνω στο δίκτυο. Το δίκτυο ηλεκτρικής ενέργειας είναι εξαιρετικά πολύπλοκο και έχει πολλούς περιορισμός στην μεταφορά ενέργειας, όπως θερμικούς περιορισμούς (thermal constrains), περιορισμούς τάσης (voltage constrains) και άλλα.

Φυσικά τίποτα από όλα αυτά δεν θα ήταν εφικτό αν δεν υπήρχε η σύγχρονη τεχνολογία να το υποστηρίξει. Τα έξυπνα δίκτυα χρησιμοποιούν τελευταίας γενιάς τεχνολογίες όπως παρακολούθηση και έλεγχος σε πραγματικό χρόνο μεγάλων περιοχών, προηγμένες υποδομές μέτρησης, συστήματα ανταπόκρισης στη ζήτηση, εφαρμογές ενίσχυσης του συστήματος μεταφοράς και άλλα.

Τα έξυπνα δίκτυα επόμενης γενιάς οδηγούνται από σύγχρονες προκλήσεις όπως συνεχής αύξηση ζήτησης ενέργειας, ανανεώσιμες πηγές, απώλειες ενέργειας του συστήματος μεταφοράς, ηλεκτρικά οχήματα αλλά και αξιοπιστία του δικτύου.

Τα έξυπνα δίκτυα μπορούν να εισάγουν αποκεντρωμένες πηγές ανανεώσιμης ενέργειας. Επίσης είναι αυτά που μπορούν να συντονίσουν παραγωγούς, καταναλωτές αλλά και άλλους συμμετέχοντες στην αγορά, όπως για παράδειγμα ότι αφορά στην μετάδοση της ενέργειας στο δίκτυο και την κατανομή στους τελικούς καταναλωτές. Και τέλος τα έξυπνα δίκτυα μπορούν να διαδραματίσουν έναν ακόμα πολύ σημαντικό ρόλο, αυτόν της αντιμετώπισης των σύγχρονων περιβαλλοντικών προκλήσεων.

Τελικά η μεγαλύτερη διασύνδεση μέσω των δικτύων, οι ανανεώσιμες πηγές ενέργειας αλλά και η ζήτηση που καθοδηγείται από την τιμή της ηλεκτρικής ενέργειας είναι αυτά που μετατρέπουν τα συμβατικά δίκτυα ηλεκτρικής ενέργειας σε έξυπνα δίκτυα επόμενης γενιάς.

Abstract

In this thesis, it is going to be presented the economics need it for the restructuring of the competitive electricity market. A pool-based, short-term, competitive electricity market coordinated by a system operator, radically changes the traditional way markets work. Consumers play a significant role in the electricity market restructuring because they undertake the role of price-makers. A system operator takes bids from generators and consumers of energy in order to balance supply and demand. The notions of short-run competitive electricity market, transmission congestion costs over the grid, long-run market contracts and scheduling and balancing methods are going to be introduced.

However, the restructuring of the electricity market would not be possible without the technology development and the smart grids. Many state of the art technologies like monitoring and control, demand response systems, transmission enhancement applications, advanced metering infrastructure and of course information and communication technologies, provide the grid with all these tools needed it, in order to meet the growing challenges of today and they are going to be analyzed in this thesis.

Greater interconnectedness, renewable energy and price-directed demand drive the evolution of the conventional power grids towards intelligent power networks.

"When Smart Grid implementation becomes reality, everyone wins – and what were once our risks become our strengths" (U.S. Department of Energy).

CONTENTS

1. Introduction

Electricity systems worldwide face a number of challenges, including ageing infrastructure, continued growth in demand, shifting load patterns, the need to integrate new sources of supply and the variability of some sources of renewable-based supply. Line loss, greenhouse gas emissions, fuel costs, regulatory concerns, government mandates and myriad other issues necessitate another look at how electricity is generated and delivered. Offering 99% reliability is no longer sufficient to serve the needs of a highly technological society. Combined with other emerging trends, the increasing global population and the growing development of renewables will place substantial stress on a grid that was designed many years ago.

Smart-grid technologies offer a cost-effective means of helping to meet these challenges and contribute to the establishment of an energy system that is more energy efficient, more secure and more sustainable.

Still, energy and where to find it, for an increasingly energy-hungry world, is going to be an issue moving forward, and so will be the management of the energy we have. On October 31, 2011, the estimated world population reached 7 billion people, and it is growing at a rate of about 215,120 people per day. Large numbers of people - particularly in China and India - are moving into the middle class and can now afford luxuries, such as refrigerators and air conditioners. More factories are needed to manufacture these products, more businesses are needed to sell them and more service providers are needed to cater to them. As a consequence, new and larger demands are being made for electric power, and new electric infrastructure is being built.

The fundamental issue of the smart grid is a seamless system that provides electricity supply and demand all the time. In the competitive electricity market large numbers of producers compete with each other to satisfy the wants and needs of a large number of consumers. Consumers help balance supply and demand, and ensure reliability by modifying the way they use and purchase electricity. Customers have demands that are sensitive to price, and higher prices produce lower demands. In this way, we reach a point where the quantity demanded by consumers at current price will equal the quantity supplied by producers.

Greater interconnectedness, renewables and price-directed demand drive the evolution of the conventional power grids towards intelligent power networks.

In this thesis, it is going to be presented in chapter two how the way of living in our contemporary world challenges the traditional grid and how these challenges are the drivers for developing a smart power grid. In addition to that, smart grid technologies are going to be presented and analyzed. In chapter three, basic economics of supply, demand and market equilibrium will be presented and also types of markets are going to be analyzed. In chapter four, it is going to be presented all the energy economics needed for restructuring the electricity market, in order to build a wholesale competitive electricity market coordinated by a system operator. The basic idea of the wholesale competitive electricity market is that of balancing supply and demand of electricity in an optimal way that benefits both producers and consumers of energy. In the competitive electricity market, as it is going to be analyzed in chapter four, consumers are “price makers” and generators of energy are “price takers”, which is something that changes radically the “rules” of the electricity markets.

The evolution of the information and communication technologies and the smart grids gives as the capability for the total restructuring of the electricity market, in order to meet the continuous growth of electricity demand.

2. Smart Electricity Networks

The availability of reliable supplies of electricity has become increasingly essential for daily living for most people in both developed and developing countries. It lights homes and workplaces, powers computers and enables industrial activity.

Most electrical power, regardless of how it is produced or used, is transferred from generation plant to consumers through electricity networks, known as electricity grids or the grid.

To meet the demand for reliable supply, the grid must operate 24 hours a day, 365 days a year, meeting and balancing ever-changing levels of demand and supply. And it must do so in a cost-effective way, often using an ageing infrastructure. The complexity of this operation will be further complicated by steps to increase the use of electricity for both public and private transportation, the bringing on stream of greater amounts of renewable energy and other distributed generation, and increasing demand for electricity in general (IEA, 2010).

In the developing world and emerging economies, electricity demand is increasing at significant rates in response to economic and social development. Development and growth vary between regions and there continues to be a need to address energy poverty in many areas. Existing electricity systems are insufficient for today’s needs in many parts of the world. Change and investment will be required to enable further development and growth.

The changes projected in electricity generation and demand, both in the IEA Baseline scenario and the IEA BLUE Map scenario in 2050 (see APPENDIX for scenario descriptions), will require an enormous investment in the electricity grid. Investment in so-called smart grid technologies will be fundamental to enabling these changes.

2.1 History of the Grid

The electricity grid has traditionally been developed, designed and implemented in such a way that electricity flows one-way from large generators to widely distributed loads. This highly structured and centralized approach has drawbacks at three distinct levels in the system (IEA, 2010):

- “Distribution system operators have little or no detailed information on the demand from different sectors or nodes on the grid. So, for example, when a residential power outage occurs, the supply utility typically only becomes aware of it when consumers phone to ask what is happening.

- Transmission system operators have more intelligence about changes in demand and supply on the network. But this is still insufficient at times to allow utilities to anticipate or receive prior warning of developing problems. This limits the extent to which generators can proactively dispatch grid support or isolate minor problems so as to prevent the sort of large-scale outages that have been seen in the United States, Canada and Italy in recent years.

- Many end users are billed according to the amount of electricity they have used over an extended time period. They, therefore, have no access to detailed information on how or when they are using electricity. So they have no means of readily identifying ways of reducing or shifting their electricity use to minimize their demand and costs” (IEA, 2010).

These are all challenging weaknesses in the traditional electricity grid. They need to be met by the implementation of new technology and methodologies for the design, maintenance and operation of electricity distribution systems. These need to be better adapted to modern circumstances, such as the emerging growth in consumers wanting to generate their own electricity with the option to sell any excess generation back to the grid.

Developing countries may have the opportunity to make early technological leaps to the implementation of smart grids, without going through the extensive development of traditional grids. This will enable them to benefit from these new technologies early in the implementation of a more widespread electricity infrastructure.

2.2 The traditional grid challenged

2.2.1 Electricity demand

Worldwide electricity demand is expected to more than double between 2007 and 2050. In the Baseline scenario (see APPENDIX A), demand increases by 151% and in the BLUE Map scenario (see APPENDIX A) it increases by 117%. This increase is not spread equally across regions. Those regions that currently have small electrical demands will see the largest growth between 2007 and 2050 (Figure 1).

The need for grid maintenance and expansion will be different for those regions with high growth than for those with low growth. The three areas with projected low growth (OECD North America, OECD Europe and OECD Pacific) are areas that have a large legacy infrastructure that is ageing, the replacement of which is constrained by regulatory regimes which set limits on capital expenditure. In areas with greater growth, primarily non-OECD member countries, ageing infrastructure and reliability are also of concern. But these regions will also be committing to new construction, providing an opportunity to deploy modern electricity grid technology and to learn from the experience of other regions. The best way forward in some cases may be to render existing unreliable or inflexible infrastructure redundant (IEA, 2010).

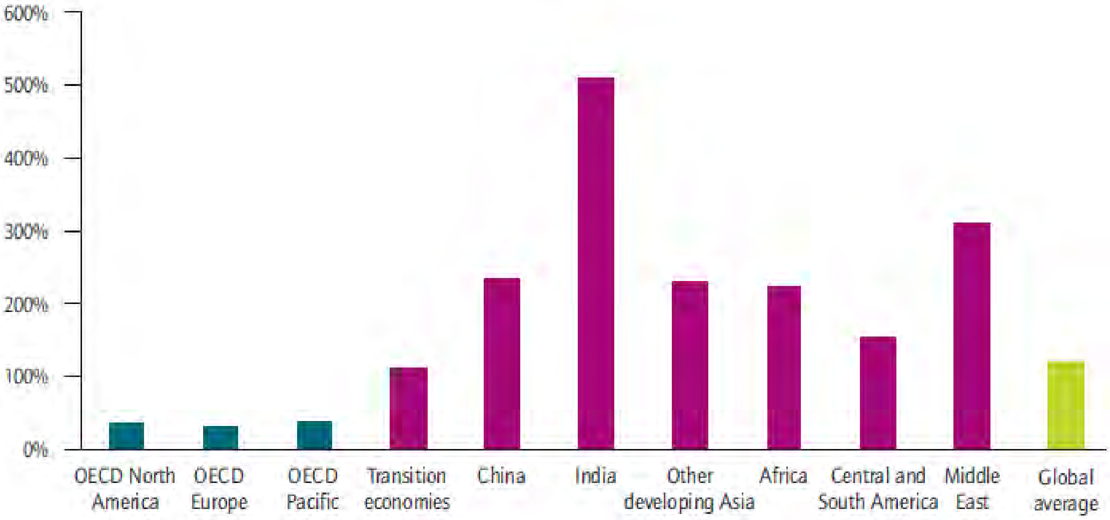


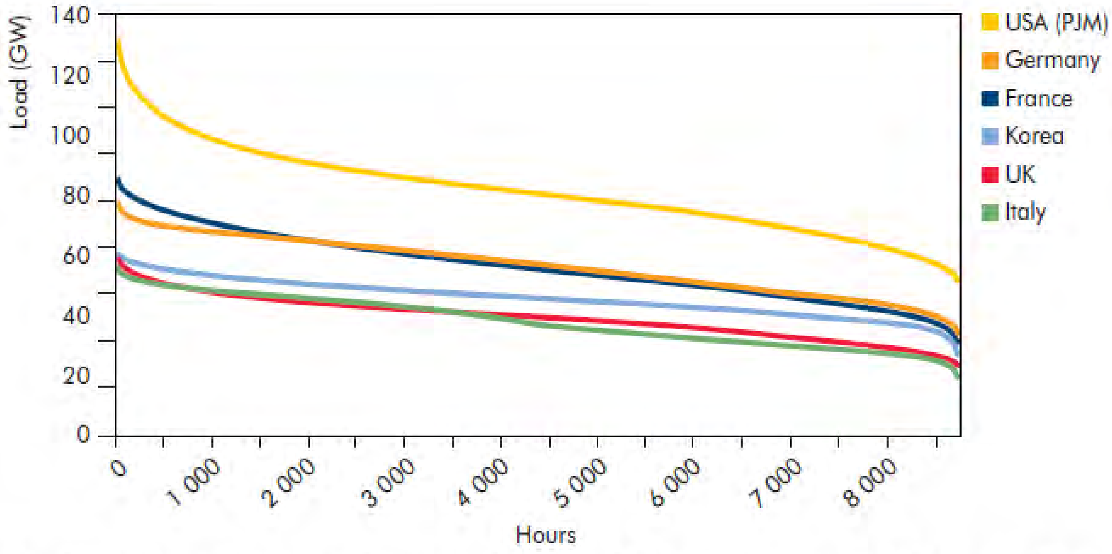
Figure 1: Electricity consumption growth 2007-50 (Source: Technology Roadmap - Smart Grids, OECD/IEA, 2011)

2.2.2 Demand profiles - Peak demand

The amount of electrical power required on any system fluctuates throughout the day. It also varies over the course of the year between a minimum base load and peak load. This aspect is demonstrated by load duration curves that show the number of hours that a given average hourly load occurs in an electricity system over the course of a year (Figure 2).

These data show that the minimum demand on the system in selected countries and regions is less than half of the peak demand. The generation, transmission and distribution infrastructure must be designed in a way that it can work reliably within this entire range. “In France, for example, the peak 10% of generating capacity is only required 3% of the time. And about 20% of the total demand over a year is supplied by plants that operate just over 15% of the time. Securing private funding for investment in generation capacity to meet peak demand can be difficult if market structures do not provide revenue security for such high value, low call-off generation” (IEA, 2010).

Baseload is also becoming more important for system management. For many years, base load was supplied by large fossil or nuclear plants from which output remained virtually constant throughout the year. Recently, fluctuations in electricity supply and demand have required large-scale base load plants to curtail and then increase their generation output. As a result, there is new interest in developing technologies that can enable these plants to provide responsive and flexible generation (Schmitt 2009).



Note: PJM is a Regional Transmission Organisation which is part of the Eastern Interconnection Grid in the United States.

Figure 2: Load duration curves for several countries in 2008 (Source: IEA - Energy Technology Perspectives, 2010)

We see how the annual electricity demand on the overall systems varies significantly across the year.

Residential and service sector demand varies over the course of the day and between seasons (Figure 3).

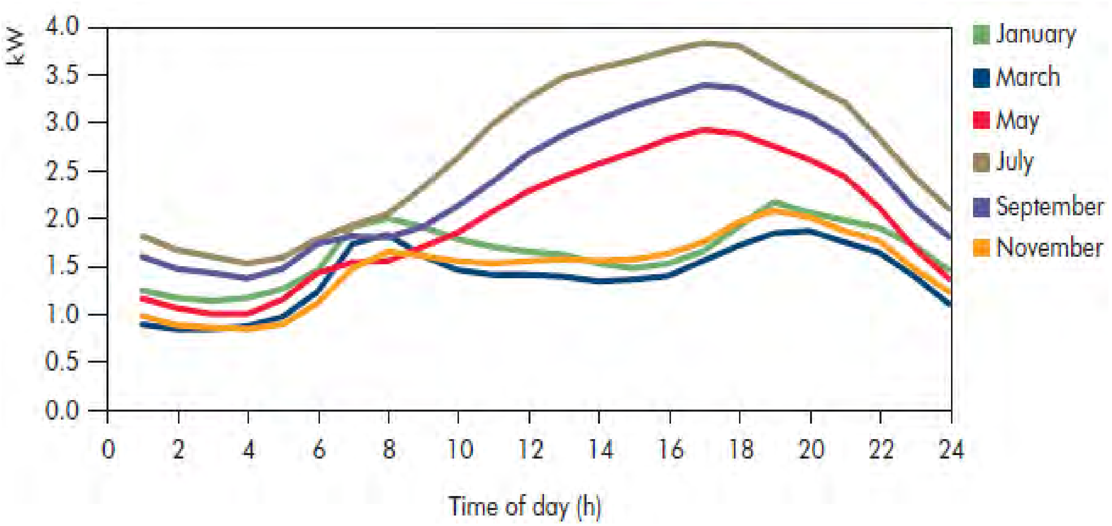


Figure 3: Daily average residential electricity demand in a sample of homes in Florida, United States with a high penetration of central air-conditioning load (Source: Parker, 2002)

The curves in Figure 3 represent a region with large amounts of residential central air-conditioning. It would not be representative of many areas in Europe that have much lower levels of central air-conditioning.

"The degree to which sector-specific peak demand affects overall electrical systems is dependent on its share of the overall electricity power demand. Industrial sectors, for example, often make up a large percentage of the electricity demand and contractual arrangements are often put in place to curtail their demand in circumstances where the grid needs to reduce peak demand. As sector demand patterns change in future, with increased residential loads and/or the wider electrification of transportation, peaks may become more difficult to manage" (IEA, 2010).

2.2.3 Electricity Generation - Renewable Energy

Climate change has raised awareness of the effects of increased carbon emissions and has focused attention on the negative externalities of the use of electricity and its energy sources. Electricity production causes about 40% of Europe's output of GHG emissions (Eskeland, Rive & Mideksa, 2008).

There will be significant changes in the way electricity is generated in the future. In addition to large centralized power plants, distributed generation in the form of both renewable and non-renewable generation is increasing, including plants connected directly to the distribution system and micro-generation at the household level.

Variable renewable energy (varRE) technologies such as wind, solar PV, run of river hydro and tidal, present particular challenges to the transmission system (Figure 4). Unlike non-variable power generation, where the generation can be contracted and dispatched with high degrees of certainty over long time frames and where the fluctuations can be managed in a controlled manner, varRE generation is difficult for system operators to predict both in terms of the uncertainty of its availability and the short time frame in which the speed and magnitude of any fluctuations can be predicted (Boyle, 2009).

"In many electricity systems, merit orders require that all available renewable power is used at all times in order to minimize generation emissions or variable costs. This means the grid operator needs to manage the available non-variable generation to respond to changes in supply from the varRE generation and to meet a constantly changing level of demand, so as to maintain grid stability and reliability of supply" (IEA, 2010).

Bioenergy, hydropower with water storage, geothermal and concentrating solar power generation with thermal storage would be considered as non-variable forms of renewable energy (IEA, 2010).

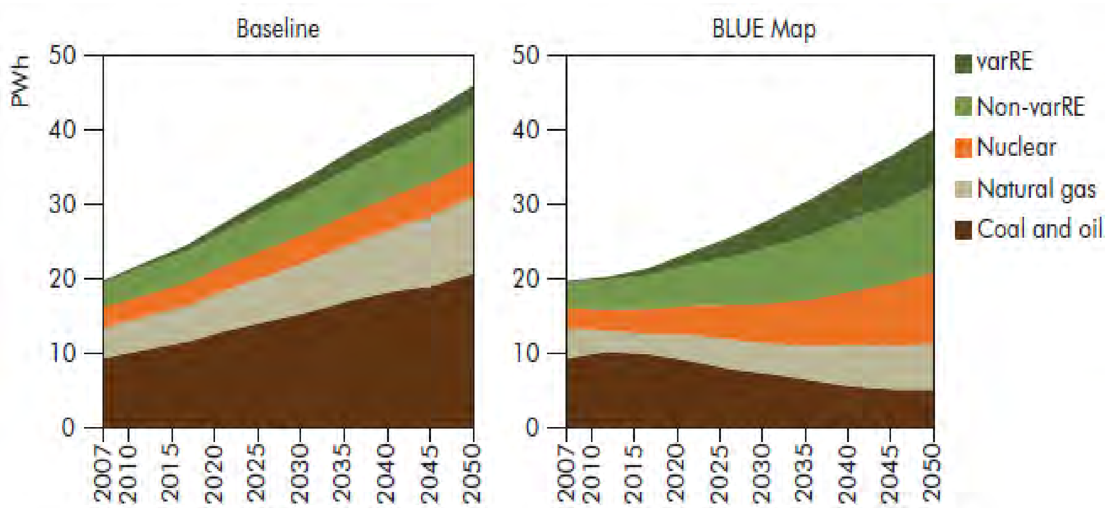


Figure 4: Global electricity generation mix (Source: IEA - Energy Technology Perspectives, 2010)

In the BLUE Map scenario, the progressive decarbonisation of electricity generation leads to varRE generation making up 19% of all generation. This proportion ranges from 10% to 27% by region by 2050 (Figure 5).

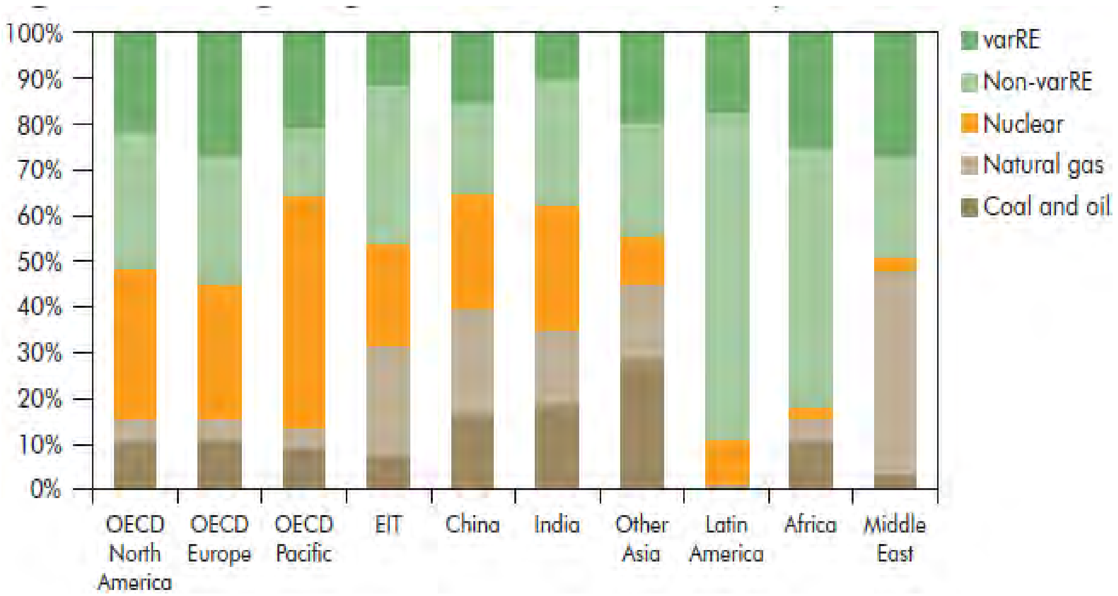


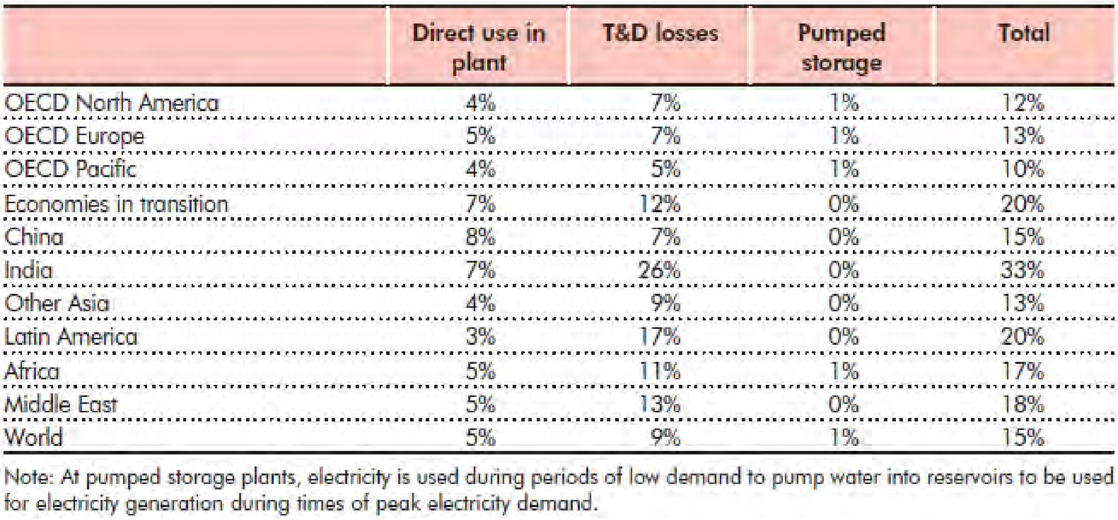
Figure 5: Regional generation mix in 2050, BLUE Map scenario (Source: IEA - Energy Technology Perspectives, 2010)

Areas with higher amounts of varRE will need grid systems designed to handle their variability. Regions that may intend to move to higher levels of varRE will need to plan for that as they upgrade and develop their grid systems.

2.2.4 Electricity Network Losses

In the electricity system, more electricity is produced than is actually consumed by end users. The balance is lost primarily through direct use in generation plants, through transmission and distribution (T&D) losses and through electricity storage inefficiency (Table 1).

Table 1: Regional electricity system use and loss of electricity, 2007



	Direct use in plant	T&D losses	Pumped storage	Total
OECD North America	4%	7%	1%	12%
OECD Europe	5%	7%	1%	13%
OECD Pacific	4%	5%	1%	10%
Economies in transition	7%	12%	0%	20%
China	8%	7%	0%	15%
India	7%	26%	0%	33%
Other Asia	4%	9%	0%	13%
Latin America	3%	17%	0%	20%
Africa	5%	11%	1%	17%
Middle East	5%	13%	0%	18%
World	5%	9%	1%	15%

Note: At pumped storage plants, electricity is used during periods of low demand to pump water into reservoirs to be used for electricity generation during times of peak electricity demand.

Source: IEA - Energy Technology Perspectives, 2010

Electricity used in generation plants ranges from 3.0% to 8.3%. It can be reduced by system improvements and modernization at the plant. T&D losses are larger, accounting for more than 9% of all generation worldwide, and vary much more between regions. OECD countries and China have the lowest percentage T&D losses, ranging from 5.0% to 7.2%. Even so, these losses represent a large amount of electricity, equivalent to more than the T&D losses from all other regions combined. In non-OECD countries T&D losses are higher as a percentage of total generation.

Many of these losses can be reduced by the modernization of the electricity grid. Better system level and end-use metering in particular will enable the losses to be identified and resolved.

2.2.5 Electrification of transport

The BLUE Map Scenario estimates that the transport sector will make up 10% of overall electricity consumption by 2050 because of a significant increase in electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV) (Figure 6). If vehicle charging is not managed intelligently, it could increase peak loading on the electricity infrastructure, adding to current peak demands found in the residential and service sectors, and requiring major infrastructure investment to avoid supply failure.

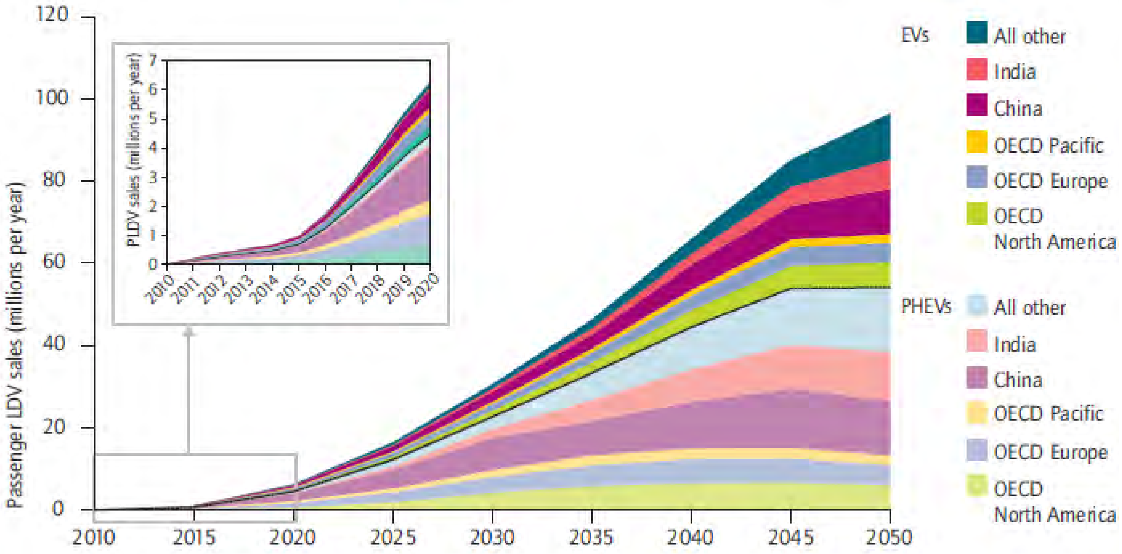


Figure 6: Deployment of electric vehicles and plug-in hybrid electric vehicles (Source: Technology Roadmap - Smart Grids, OECD/IEA, 2011)

2.2.6 Ageing Infrastructure

The electrification of developed countries has occurred over the last 100 years. As demand grows and changes (e.g. through deployment of electric vehicles), and distributed generation becomes more widespread, ageing distribution and transmission infrastructure will need to be replaced and updated, and new technologies will need to be deployed. Unfortunately, in many regions, the necessary technology investment is prevented by existing market and regulatory structures, which often have long approval processes. Smart grid technologies provide an opportunity to maximize the use of existing infrastructure through better monitoring and management, while new infrastructure can be more strategically deployed (OECD/IEA, 2011).

2.2.7 Electricity Reliability

In the United States there have been five massive blackouts over the past 40 years, three of which have occurred in the past nine years. More blackouts and brownouts are occurring due to the slow response times of mechanical switches, a lack of automated analytics, and “poor visibility” – a “lack of situational awareness” on the part of grid operators. This issue of blackouts has far broader implications than simply waiting for the lights to come on. Imagine plant production stopped, perishable food spoiling, traffic lights dark, and credit card transactions rendered inoperable. Such are the effects of even a short regional blackout. Also, in many areas of the United States, the only way a utility knows there’s an outage is when a customer calls to report it (U.S. Department of Energy).

And what is the cost of these outages? The numbers are staggering and speak for themselves:

- A rolling blackout across Silicon Valley totaled $75 million in losses.
- In 2000, the one-hour outage that hit the Chicago Board of Trade resulted in $20 trillion in trades delayed.
- Sun Microsystems estimates that a blackout costs the company $1 million every minute.
- The Northeast blackout of 2003 resulted in a $6 billion economic loss to the region.

2.3 Vision for the grid of the future - Smart Grid

2.3.1 Power System Flexibility

A flexible power system can both supplement periods of low variable generation to meet demand as required, and manage large surpluses when demand is low. A flexible system is one which is able to transport, store, trade and consume electricity to maintain reliable supply in the face of rapid changes and potentially very large imbalances in supply and demand (IEA, 2010).

Power systems worldwide vary enormously in terms of scale, interconnection, generation, storage, transmission and distribution, demand behavior, and market rules. The most appropriate way to handle large-scale variable renewable energy shares will depend on the specific characteristics of the overall system into which the renewable energy is being supplied.

"Power systems can be adapted in a number of ways to provide more flexibility to balance variable generation including:

- Increasing the size of balancing areas – to enable a geographically larger area to rely on a smaller proportion of reserve generation capacity to maintain system reliability, to enable imbalances to be resolved where they cost least, and to take advantage of the smoother average generation that is likely to result from a large geographic spread of renewable energy.

- Demand shaping through demand-side management – using prices to move some demand from peak to off-peak periods.

- Improving output forecasting and intra-hour dispatch – to allow more efficient scheduling of flexible reserves.

- Increasing control of transmission and distribution assets – to increase transmission capacity and reduce congestion during key periods and over critical line lengths" (IEA, 2010).

"Once all the options for optimizing the use of existing flexibility resources of a system have been exhausted, still larger amounts of renewable energy generation will need to be balanced by increased capacity of these resources. Such measures may include additional flexible power plant capacity; additional storage capacity; the reinforcement and expansion of transmission and distribution networks; and interconnection between adjacent grid areas" (IEA, 2010).

2.3.2 Electricity Grid of the Future - What is a Smart Grid?

Growth and change in the electricity system over the next 50 years will require major investment. The electricity grid of the future will need to demonstrate the same primary functional characteristics as today. But it will need to accomplish this with added flexibility in order to enable an environment with a different mix of both centralized and distributed, non-variable and variable generation and new demand profiles. In order for the grid to operate optimally in this environment, there will be a need for the grid to become more intelligent, i.e. to become smarter (IEA, 2010).

What is a smart grid? To understand what is and what is not, it is useful to look at Van de Putte's (2011) definition of the 3 types of intelligent grids: micro grids, smart grids and super grids.

- Micro grids often cover islands, small towns or districts, where the distribution network incorporates monitoring and control infrastructure and uses local energy generation sources. The objective of a micro grid is to supply local power needs as efficiently as possible.

- Smart grids balance supply and demand out over a region. They use advanced types of control and management technologies to efficiently distribute power and connect decentralized renewable energy sources and cogeneration to the grid.

- Super grids transport large energy loads between regions or countries with large supply and large demand, using HVDC technology based interconnections.

A smart grid (Figure 7) is an electricity network that uses digital technology to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users. Such grids will be able to coordinate the needs and capabilities of all generators, grid operators, end users and electricity market participants in such a way that it can optimize operation and minimize costs and environmental impacts. Also they should maintain system reliability and stability (OECD/IEA, 2011).

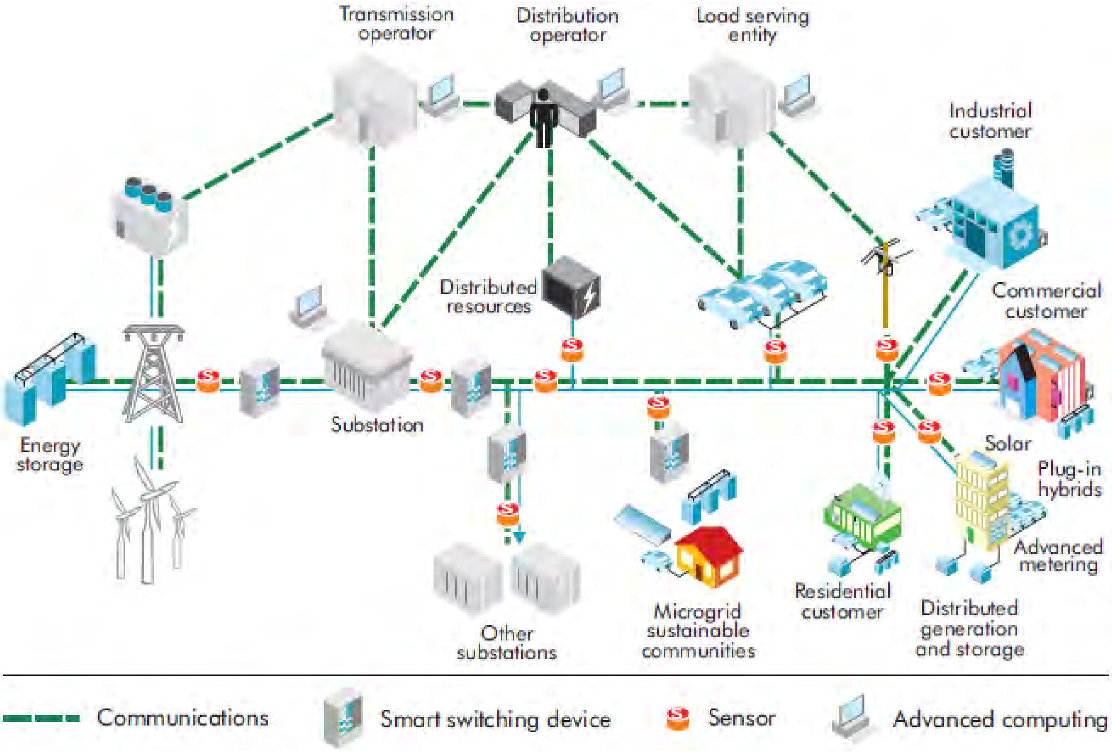


Figure 7: A Smart Grid (Source: Wang, 2009)

2.3.3 From hierarchy to network

Today's power systems are designed to support large generation plants that serve faraway consumers via a transmission and distribution system that is essentially one-way. But the grid of the future will necessarily be a two-way system where power generated by a multitude of small, distributed sources — in addition to large plants — lows across a grid based on a network rather than a hierarchical structure (Figure 8).

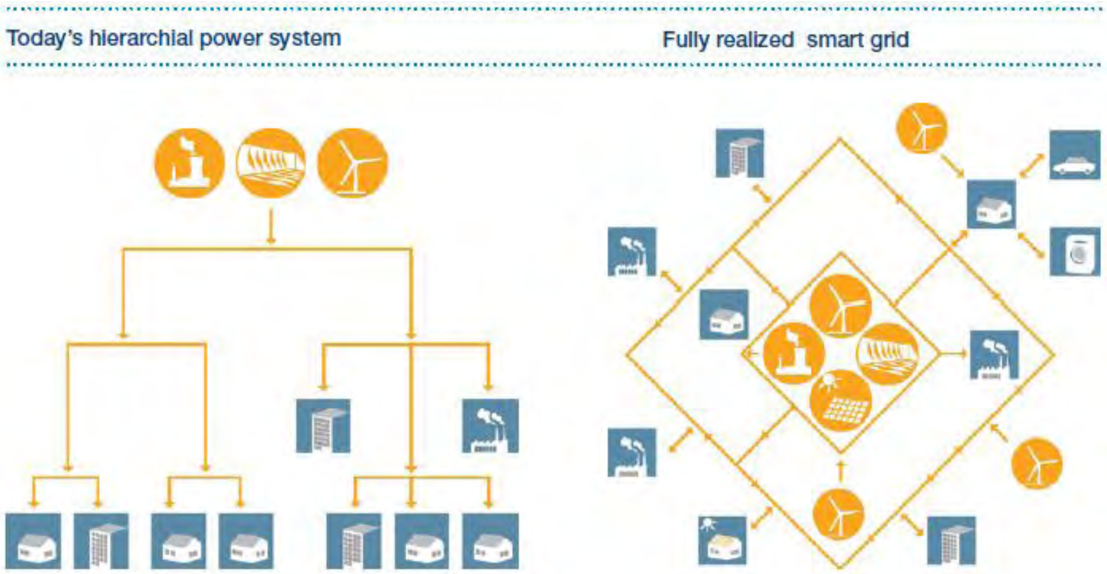


Figure 8: From hierarchy to network (Source: ABB, 2009)

The diagrams in Figure 8 illustrate this shift. In the first, we see today's hierarchical power system, which looks much like an organizational chart with the large generator at the top and consumers at the bottom. The second diagram shows a network structure characteristic of a fully implemented smart grid. We can also see this shifting in Figure 9.

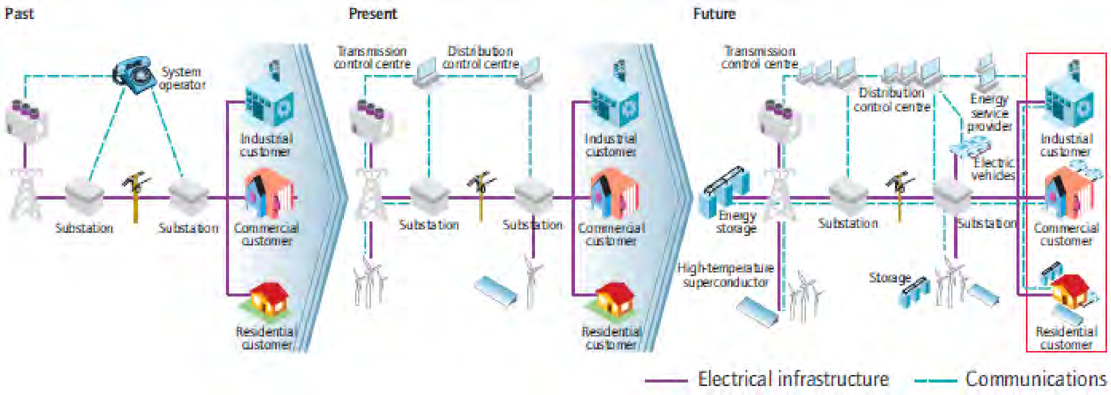
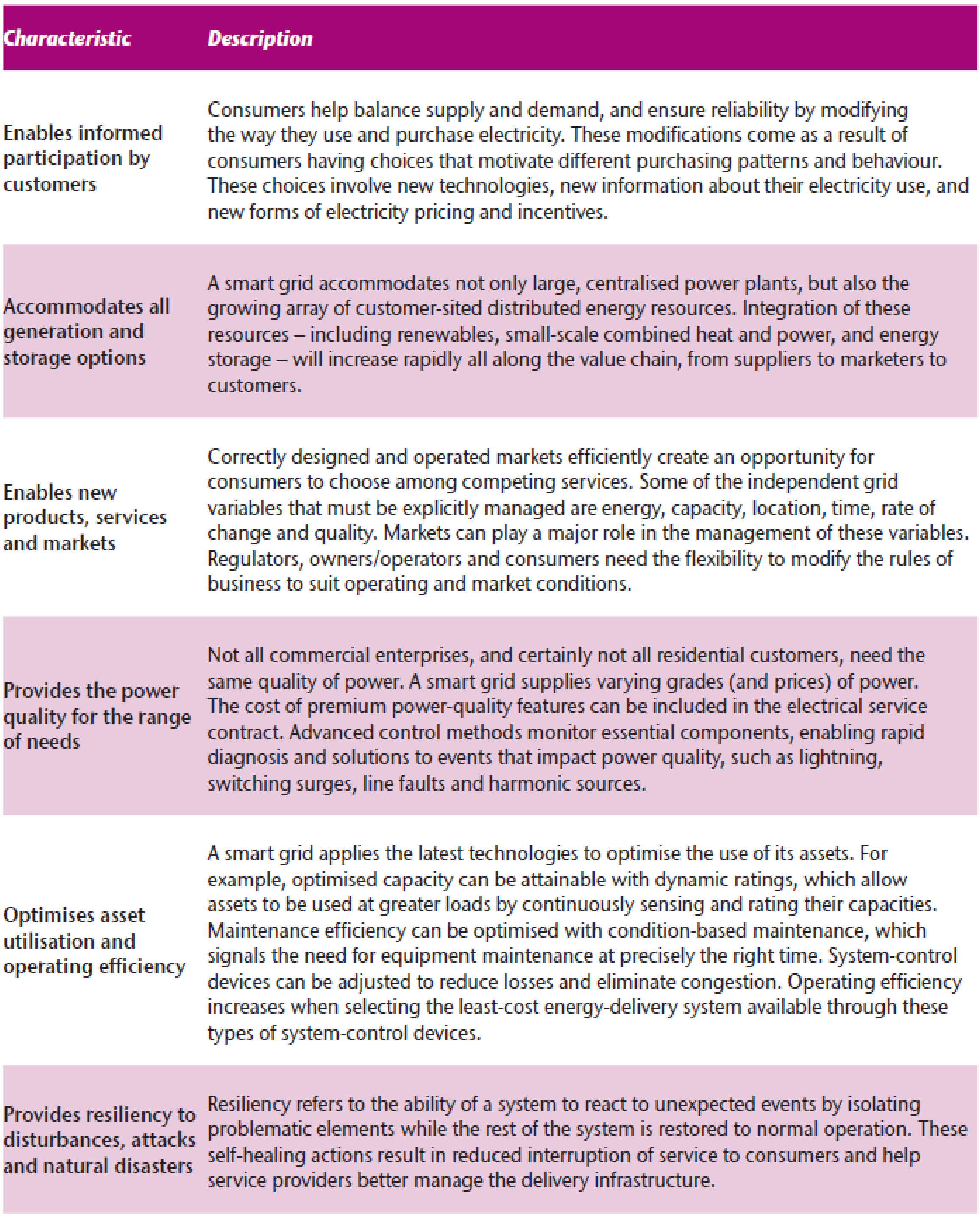


Figure 9: Past, Present and Future (Source: IEA, 2011)

2.3.4 Smart Grid Characteristics

The grid is an enabler. It enables sources of generation to be linked to consumers. A range of technologies are primarily grid related, as distinct from being generation related or consumer related (Table 2).

Table 2: Smart Grid Characteristics



Characteristic	***Description***
Enables informed participation by customers	Consumers help balance supply and demand, and ensure reliability by modifying the way they use and purchase electricity. These modifications come as a result of consumers having choices that motivate different purchasing patterns and behaviour. These choices involve new technologies, new information about their electricity use, and new forms of electricity pricing and incentives.
Accommodates all generation and storage options	A smart grid accommodates not only large, centralised power plants, but also the growing array of customer-sited distributed energy resources. Integration of these resources – including renewables, small-scale combined heat and power, and energy storage – will increase rapidly all along the value chain, from suppliers to marketers to customers.
Enables new products, services and markets	Correctly designed and operated markets efficiently create an opportunity for consumers to choose among competing services. Some of the independent grid variables that must be explicitly managed are energy, capacity, location, time, rate of change and quality. Markets can play a major role in the management of these variables. Regulators, owners/operators and consumers need the flexibility to modify the rules of business to suit operating and market conditions.
Provides the power quality for the range of needs	Not all commercial enterprises, and certainly not all residential customers, need the same quality of power. A smart grid supplies varying grades (and prices) of power. The cost of premium power-quality features can be included in the electrical service contract. Advanced control methods monitor essential components, enabling rapid diagnosis and solutions to events that impact power quality, such as lightning, switching surges, line faults and harmonic sources.
Optimises asset utilisation and operating efficiency	A smart grid applies the latest technologies to optimise the use of its assets. For example, optimised capacity can be attainable with dynamic ratings, which allow assets to be used at greater loads by continuously sensing and rating their capacities. Maintenance efficiency can be optimised with condition-based maintenance, which signals the need for equipment maintenance at precisely the right time. System-control devices can be adjusted to reduce losses and eliminate congestion. Operating efficiency increases when selecting the least-cost energy-delivery system available through these types of system-control devices.
Provides resiliency to disturbances, attacks and natural disasters	Resiliency refers to the ability of a system to react to unexpected events by isolating problematic elements while the rest of the system is restored to normal operation. These self-healing actions result in reduced interruption of service to consumers and help service providers better manage the delivery infrastructure.

Source: Technology Roadmap - Smart Grids, OECD/IEA, 2011

2.4 Smart Grids Technologies

The many smart grid technology areas – each consisting of sets of individual technologies – span the entire grid, from generation through transmission and distribution to various types of electricity consumers. Some of the technologies are being deployed and are considered to work well in their development and application, while others require further development. A fully optimized electricity system will deploy all the technology areas in Figure 10. However, not all technology areas need to be installed to increase the "smartness" of the grid.

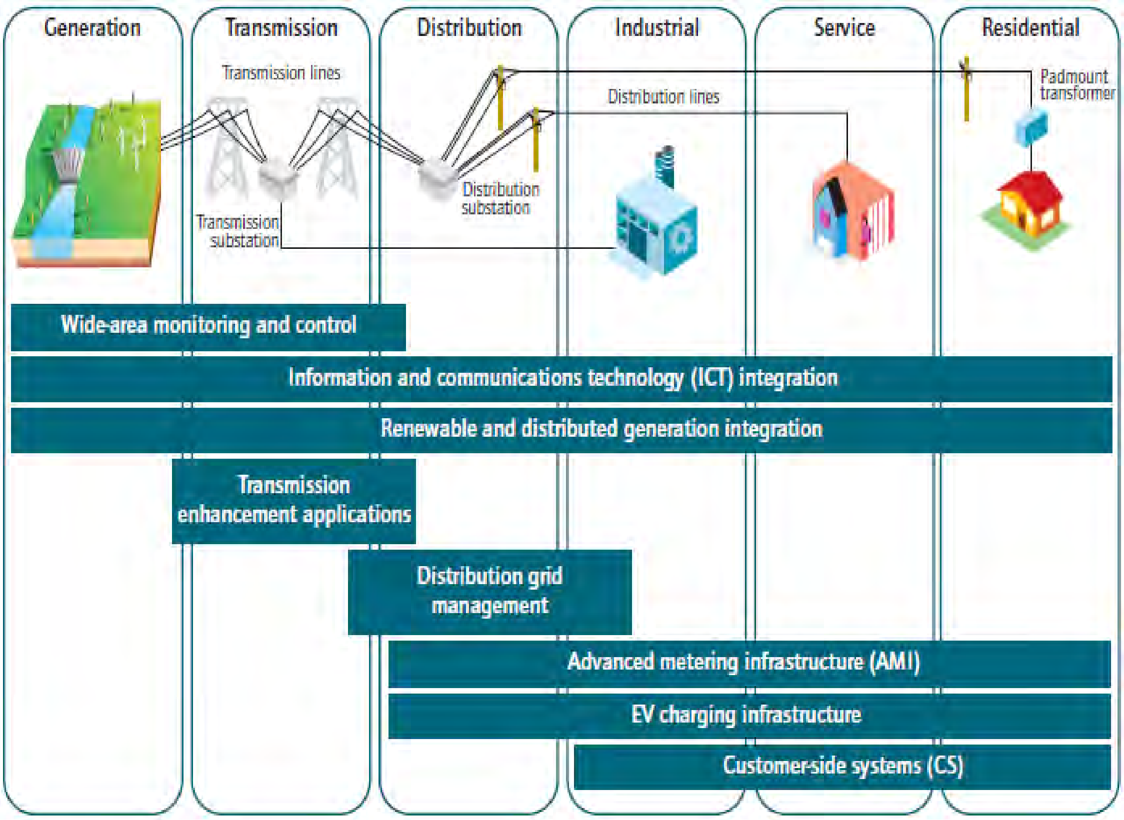


Figure 10: Smart grid technology areas (Source: Technology Roadmap - Smart Grids, OECD/IEA, 2011)

The smart grid technologies are:

(According to U.S. Department of Energy - NETL, 2010 and U.S. Department of Commerce - NIST, 2010).

- Wide-area monitoring and control
- Advanced metering Infrastructure (AMI) - The two-way information
- Information and communications technology integration
- Demand response (DR) systems
- Distributed and renewable electricity generation (DG/RES)
- Advanced energy storage
- Electric vehicles (EVs) charging infrastructure
- Transmission enhancement applications

2.4.1 Wide-area monitoring and control

Real-time monitoring and display of power system components and performance, across interconnections and over large geographic areas, help system operators to understand and optimize power system components, behavior and performance. Advanced system operation tools avoid blackouts and facilitate the integration of variable renewable energy resources. Monitoring and control technologies along with advanced system analytics – including wide-area situational awareness (WASA), wide-area monitoring systems (WAMS), and wide-area adaptive protection, control and automation (WAAPCA) – generate data to inform decision making, mitigate wide-area disturbances, and improve transmission capacity and reliability.

2.4.2 Advanced metering infrastructure (AMI) - The two-way information

Smart Meters form the basis of the intelligence of the new smart grid. The two-way information generated by advanced metering allows distribution system operators, energy retailers, energy service providers and final customers to improve their business efficiency and service performance, avoiding investments in expansion of networks and generation. Smart metering will allow utilities to offer consumers real-time or dynamic pricing, rather than static pricing. Dynamic pricing has shown to have the potential to significantly reduce peak power consumption (Faruqui, 2010). Smart metering is also a crucial capability for the integration and management of decentralized renewable energy production. In Figure 11 we can see the cumulative smart meters installation.

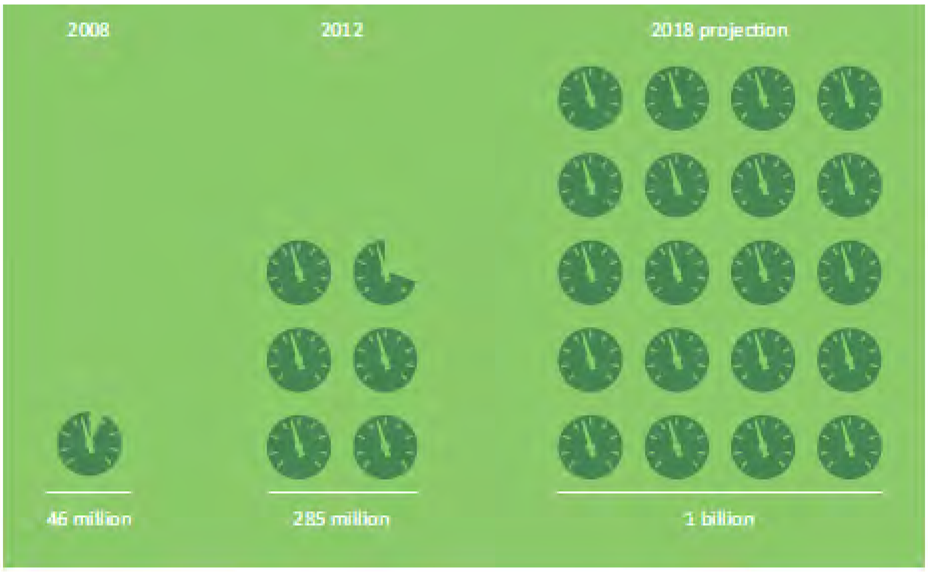


Figure 11: Cumulative smart meters installation (Source: IEA, Tracking Clean Energy Progress, 2013)

However, the smart meter on its own will not save energy. It is simply an ‘enabler’, a tool that allows for better energy management. Any smart-meter rollout involves not just the meter manufacturers but also communications companies, advanced metering infrastructure (AMI) program management, meter data management systems (MDMS) and system integration. According to research by ZPryme (Rodriguez, 2010), less than half of the market potential of AMI is made up of the meters, the rest going to the supporting technology.

2.4.3 Demand response (DR) systems

Demand response systems can help in dealing with the higher peak demand caused by e.g. EVs and renewable energy. Broadly speaking DR stands for the communication about the electricity use and price changes in the market between the utility and the consumer. Through flexible pricing at time of use, consumers can minimize their electricity bill by choosing (or letting the EMS choose) to consume at times of low prices instead of at peak demand, and utilities can balance or level the load consumption patterns. This in turn can help to avoid investments in new power plants, conserve resources and moderate energy prices.

Where today only static pricing or, at most, day/night time tariffs exist, the range of different pricing schemes will expand offering real-time or dynamic pricing to consumers. Generally three types of pricing schemes can be identified (Ekanayake, 2012):

- ToU rates: predefined, different prices for different time blocks. Its most common form is the day/night time rates. It’s the least efficient or effective in reducing peak demand.

- Real-time pricing (RTP): the electricity prices fluctuate hourly based on the wholesale electricity price. Hourly rates are announced in advance. RTP is the most efficient & effective, but is very complex and volatile.

- Critical peak pricing (CPP): a hybrid design of ToU and CPP. The basic rate structure is ToU, although utilities are earlier in informing about peak days/hours. However, the peak hour price is increased substantially.

As proven in more than 70 pilots, the reduction of peak demand in response to dynamic pricing ranges up to 58% and averages about 20%. These customer responses do persist over time with 22 some pilots operating already since 1990. Over 90% of low income customers saved money in various pilots (Faruqui, 2011).

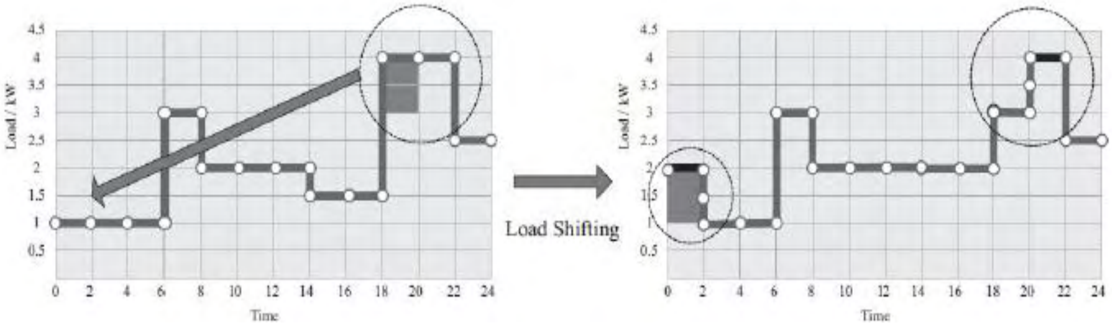


Figure 12: Load Shifting (Source: Ekanayake, 2012)

Figure 12 illustrates the case of load shifting; the demand response system causes a consumption shift between times of the day from on-peak to off-peak consumption. In this case the use of the washing machine (consuming 1kW/2h) was shifted to an off-peak period. The total energy consumption is left unchanged.

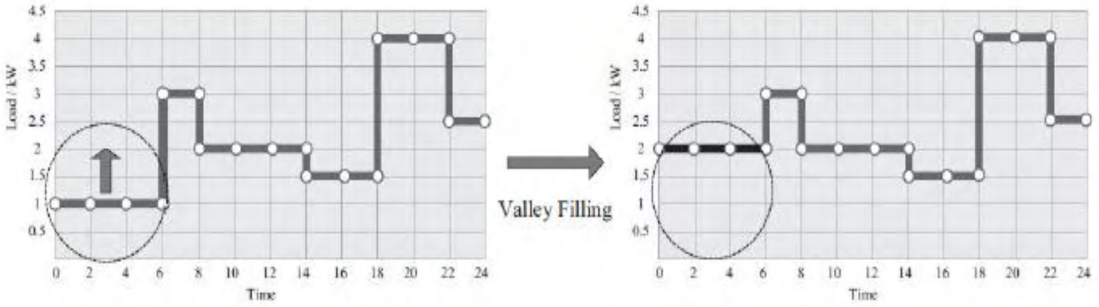


Figure 13: Valley Filling (Source: Ekanayake, 2012)

Figure 13 shows the case of valley filling. Again the goal is to decrease on-peak demand. Valley filling solves this issue by storing energy in the off-peak period in for example a plug-in electric vehicle or electric storage heater and releasing this energy in the on-peak period. However, in this case the total energy consumption has increased, as storing electricity also consumes electricity.

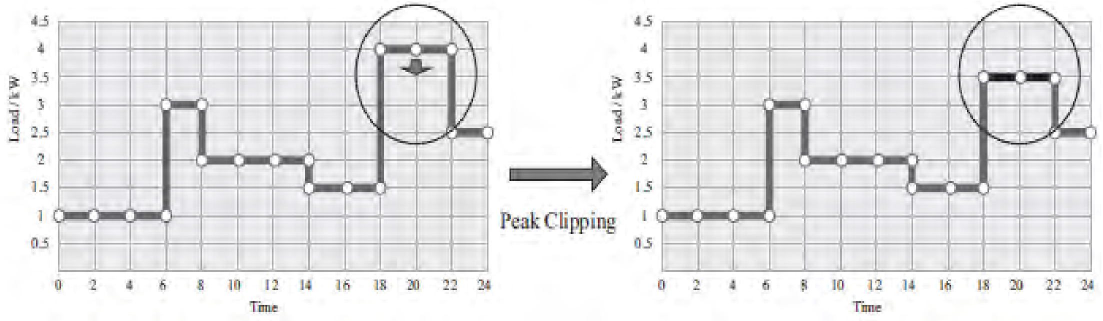


Figure 14: Peak Clipping (Source: Ekanayake, 2012)

Peak clipping reduces the peak load demand, especially when demand approaches the thermal limits of feeders/transformers, or the supply limits of the whole system. Peak clipping (Figure 14) is primarily done through direct load control of domestic appliances, for example, reducing thermostat setting of space heaters or control of electric water heaters or air-conditioning units. As peak clipping reduces the energy consumed by certain loads (in Figure 14, 2 kWh of energy is reduced), often consumers have to reduce their comfort.

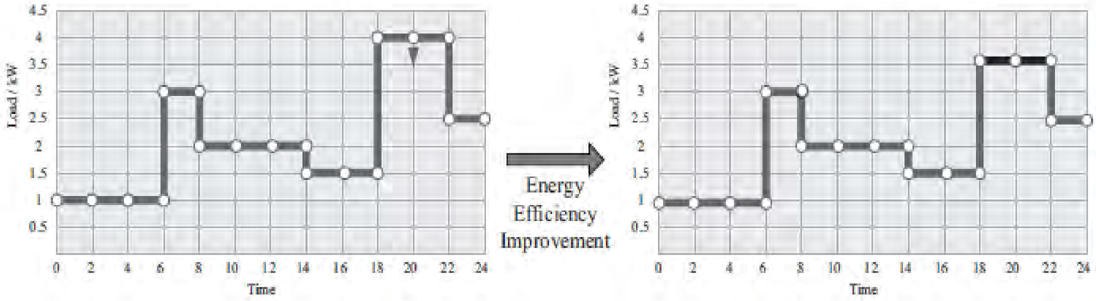


Figure 15: Energy Efficiency Improvement (Source: Ekanayake, 2012)

Energy efficiency programs are intended to reduce the overall use of energy. Approaches include offering incentives to adopt energy-efficient appliances, lighting, and other end-uses; or strategies that encourage more efficient electricity use, for example, the feedback of consumption and cost data to consumers, can lead to a reduction in total energy consumption. Figure 15 shows the reduction in energy demand when ten 60 W filament lamps (operating from 18.00 hrs to 22.00 hrs) are replaced by 20 W Compact fluorescent lamps (Ekanayake, 2012).

2.4.4 Information and communications technology integration

Underlying communications infrastructure, whether using private utility communication networks (radio networks, meter mesh networks) or public carriers and networks (Internet, cellular, cable or telephone), support data transmission for deferred and real-time operation, and during outages. Along with communication devices, significant computing, system control software and enterprise resource planning software support the two-way exchange of information between stakeholders, and enable more efficient use and management of the grid.

2.4.5 Renewable and distributed generation integration

Whereas on a traditional grid, power generation was centralized and transmission and distribution were one-way, the metering capabilities and two-way communication of smart grids enable the production of electricity in numerous, decentralized locations. The growth of renewable power production, micro- or large scale, such as the offshore wind parks, is increasing the need for a smart grid that is able to balance these intermittent resources.

Distributed generation allows electricity to be produced by utilities or by individuals, closer to the point of consumption, thus reducing energy transmission losses. It helps utilities to meet peak power needs more easily and diversify the range of energy resources, lowering the cost of distribution and increasing the reliability of the power flow (Roehr, 2010).

Distributed generation is a driver behind the reduction of electricity costs for consumers and increases the use of renewables. Power production in distributed locations can be small scale and individual “prosumers” (consumers that also micro-produce) have the option to resell their production to the utility. This is completely changing the relationship between utilities and consumers.

The development of distributed generation is driven by environmental concerns, deregulation of the electricity market, diversification of energy sources/energy autonomy and energy efficiency, while barriers are mainly technical constraints, such as design procedures, limitations on rural network capacity, fault level restrictions in urban areas and a lack of interconnection standards (ENERGnet, 2003).

2.4.6 Transmission enhancement applications

The transmission system operators (TSOs) are responsible for transmitting high-voltage electricity from producers to distribution system operators (DSOs). In many ways they are the backbone of the electricity system conveying large amounts of electric energy across borders, countries and regions. Whereas a failure in the distribution system has but little effect, a transmission equipment failure cascades into causing huge blackouts.

Transmission enhancement applications help to avoid such blackouts and achieve higher efficiency levels. Improvements also aid in coping with the integration of energy resources in remote places such as offshore windmill parks. The system employs advanced sensors in the form of e.g. phasor measurement units and new-operator simulation and visualization tools which provide better data on the situation on the ground. The improved availability of this data together with high-speed communications enable building a more dynamic management of the transmission system (Electric Power Research Institute, 2011).

2.4.7 Electric vehicle charging infrastructure

The development of electric transportation and the smart grid go hand-in-hand. Deployment of electric vehicles (EV) will be an important means to reduce society’s CO2 footprint, but also provides a very promising alternative as electricity storage capacity, feeding power back into the grid if necessary (Vehicle-to-grid V2G).

However, especially in the early stages of deployment, it is expected that electric cars will exist in clusters. If they all charge at night, it could place enormous stresses on local transformers, and it is likely that investments need to be made in transformer upgrades. In order not to increase peak power demand because of electrical cars, the battery loading patterns should be carefully planned. EV power demand could be managed through “smart charging” programs, making use of flexible pricing incentives. Another application that is being developed is “smart billing”, that allows the EV to be charged at different locations at the cost of the vehicle owner and not the property owner. Both smart charging and smart billing require a high level of communication between customer, electric car and utility, for which sophisticated software is required (van der Zanden, 2011).

2.4.8 Advanced Energy Storage

The unpredictable nature of renewable power puts different stresses on the physical grid than conventional power. The load fluctuations must be managed through automated distribution technologies, highly flexible conventional power generation or storage. The increasing penetration of renewable electricity generation sources is driving the need for energy storage. Energy storage enables utilities to supply peak demand with lower generation capacity and facilitates the integration of renewable energy sources into the grid. Future applications could include time-of-use energy cost management for the commercial and industrial segments and transmission and distribution deferral for utilities.

Grid operators with access to hydropower can store power by pumping up water behind dams and releasing it to generate power at times of high demand. Countries with no access to hydropower are experimenting with power storage in CHP (combined heat and power) plants, home heat pumps or EV (electric vehicle) batteries. Other technologies for storage include fuel cells, sodium sulphur (NAS) batteries, compressed air (CAES), flywheels and molten salt. New developments are in lithium ion batteries, ultra capacitors and flow batteries. No ideal storage solution has been developed yet and this area is being watched with great expectation (van der Zanden, 2011).

2.5 Benefits of Smart Grids

Smart grids will offer the capability (according to Gridwise Alliance):

- To reduce peak demand by actively managing consumer demand: more appliances and equipment are expected to come onto the market that can respond to both consumer and utility operator priorities. As they do, the ability to manage power requirements in both directions – to the utility as well as from the utility – will reduce the need for power. For example, during high-use periods such as hot summer afternoons when the cost of producing and delivering power is extremely high, the system will enable consumers more directly to be informed of those costs and to reduce their demand, or increase their local generation output, accordingly.

- To balance consumer reliability and power quality needs: although some uses of electricity require near perfect reliability and quality, others are almost insensitive to these needs. A smart grid will be able to distinguish differences in demand and, where appropriate, to provide less reliable and lower quality power at a reduced cost.

- To encourage the proactive application of energy efficiency opportunities: a smart grid will furnish consumers and utilities with accurate, timely and detailed information about energy use. Armed with this information, consumers will be able to identify ways of reducing energy consumption with minimal impacts on safety, comfort and security.

- To improve overall operational efficiency: smart grids will become increasingly automated and smart sensors and controls will be integral to their design and operation. Utility operators will be able more easily to identify, diagnose and correct problems, and will even have the capability to anticipate problems before they happen.

- To integrate clean energy technologies: EVs, rooftop solar systems, wind farms and storage devices will become essential parts of the grid, all contributing in a coordinated fashion to the achievement of economic and environmental goals.

3. Markets and Energy Economics

3.1 Market

Fundamentally, a market is a place where buyers and sellers meet to see and negotiate if deals can be made over commodities at that point of time or in the future.

“Market is an actual or nominal place where forces of demand and supply operate, and where buyers and sellers interact (directly or through intermediaries) to trade goods, services or contracts or instruments, for money or barter” (Business Dictionary).

“Markets include mechanisms for:

- Determining price of the traded item
- Communicating the price information
- Facilitating deals and transactions, and
- Effecting distribution

The market for a particular item is made up of existing and potential customers who need it and have the ability and willingness to pay for it”. (Business dictionary)

The Oxford dictionary of Economics defines a market as “A place or institution in which buyers and sellers of a good or asset meet”

It can be said that a market is the process by which the prices of goods and services are established.

3.2 Buyers and Sellers

3.2.1 Demand

Buyers, of course, are the parties that demand for the commodities by trading them with money or some other commodities. There are a few factors that determine the behavior of the buyers in a market which in turn affect the demand for a commodity. Among the main factors are price, quality, quantity and timing. Given that other non-price factors are precisely defined, the demand behavior is very much dependent on the price of a commodity. The quantity of a commodity bought by buyers normally increases with the decrease in the price and vice versa. In short, there is an inverse relationship between price and quantity demanded. Economists call this inverse relationship the law of demand. The demand curve is shown in Figure 16.

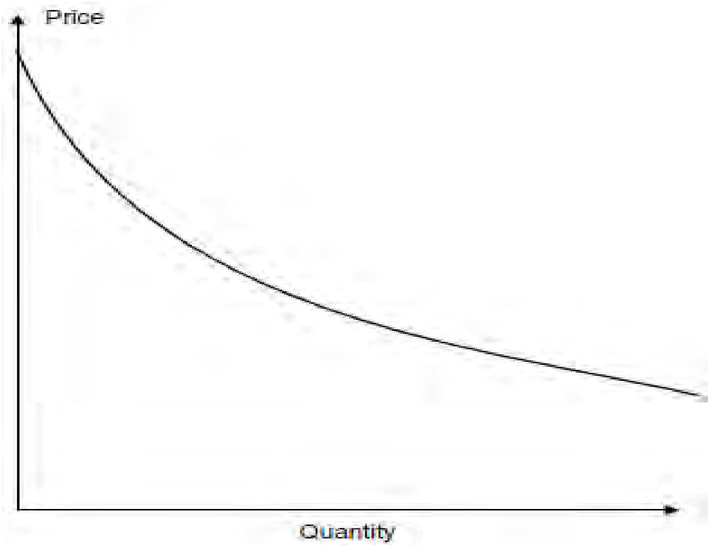


Figure 16: Demand Curve, (Kirschen and Strbac, 2004)

Figure 16 shows the typical relationship between the price of a commodity and the quantity of the demand for the commodity by the consumers. This relationship can be seen from two perspectives. The first perspective sees how the difference in commodity price can affect the quantity of the demand of the commodity. As mentioned earlier, under this perspective, the demand decreases as the price increases. This is the case when the consumers have the alternatives to one particular commodity. When the price of this commodity goes up beyond the acceptable level for the consumers, they will go for other alternative commodities which results in decreasing in quantity of demand of the first commodity.

On the other hand, the second perspective sees the relationship in Figure 16 as the price that the consumers are willing to pay to have a small additional amount of a commodity. It also tells how much money these consumers would want to receive as a compensation for a reduced consumption (Kirschen and Strbac, 2004). Considering this second perspective, from Figure 16, it indicates that the consumers or buyers are willing to pay a high price for an additional commodity if they only have a small amount of that commodity. In contrast, their marginal willingness to pay for this commodity decreases when their consumption increases.

3.2.1.1 Elasticity of Demand

Increasing the price of a commodity even by a small amount will clearly decrease demand. We can use the derivative dq/dπ of the demand curve (see Figure 16 above) to see how the demand is decreasing when the price increases. With q we represent the quantity of a commodity and with π we represent the price. Using this slope directly presents the problem that the numerical value depends on the units that we use to measure the quantity and the price. Comparing the demand's response to price changes for various commodities would be impossible. To get around this difficulty, we define the price elasticity of demand. Kirschen and Strbac define the "price elasticity of demand as the ratio of the relative change in demand to the relative change in price":

$$\varepsilon = \frac{dq/q}{d\pi/\pi} = \frac{\pi}{q} \times \frac{dq}{d\pi}$$

The demand for a commodity is said to be elastic if a given percentage change in price produces a larger percentage change in demand.

On the other hand, if the relative change in demand is smaller than the relative change in price then the demand is inelastic to the price. This is the case in certain commodities like electrical energy especially if it is viewed in a short term horizon.

3.2.1.2 Changes in Demand

A change in one or more of the determinants of demand (e.g. changing the behavior of buyers because of changes in price, quality or quantity) will change the location of the demand curve (Figure 17). Graphically, a shift in the demand curve is called a change in demand. If consumers desire to buy more of a commodity at each possible price, that increase in demand is shown as a shift of the demand curve to the right, say, from D1 to D2. Conversely, a decrease in demand occurs when consumers buy fewer of a commodity at each possible price. The leftward shift of the demand curve from D1 to D3 in Figure 17 shows that situation.

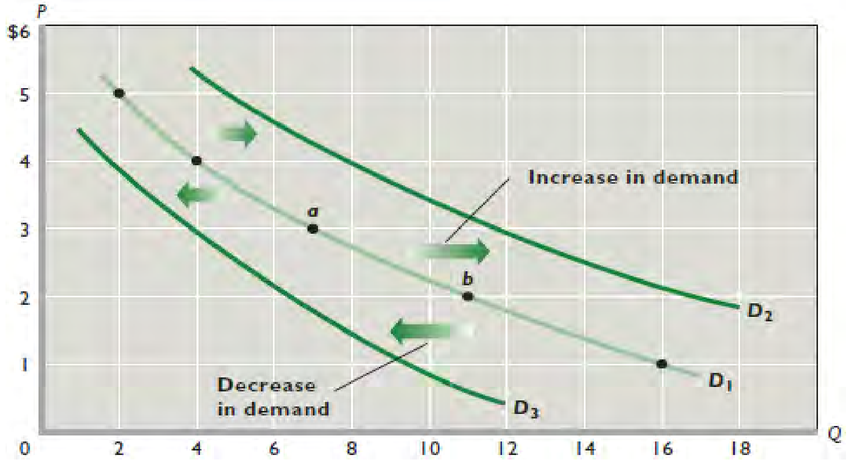


Figure 17: Changes in the Demand (McConnell Brief)

3.2.2 Supply

As for the sellers, they are a group of parties that produce or supply the commodities or services to the buyers. The behavior of the suppliers and hence the supply of a commodity is also very much related to the market price. The volume of supply of a commodity in a market will go higher when the market price is high enough relative to the production cost. This is because the producers or the suppliers will find it worthwhile to increase their production of a commodity when the market price is high. This definitely affects the quantity of commodity that is available to be sold to the buyers in the market.

The relationship between quantities of supply of a commodity in a market with the market price is given by the supply curve graph as shown in Figure 18.

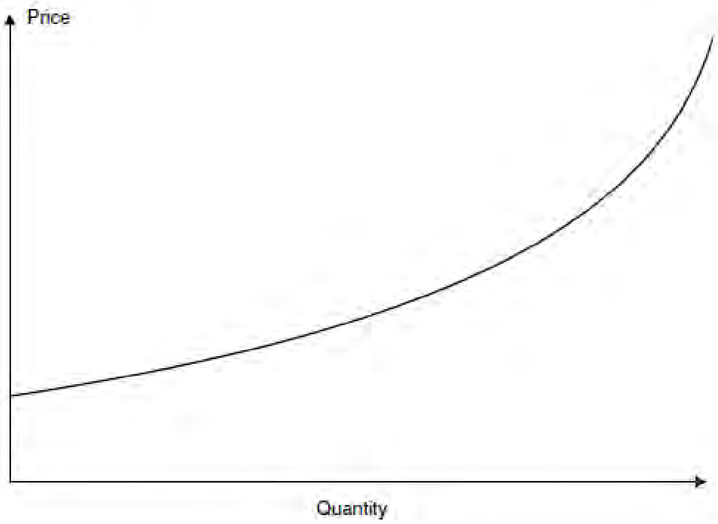


Figure 18: Supply Curve (Kirschen and Strbac, 2004)

In Figure 19 below, commodities produced by different producers are tabulated along the supply curve. This will break the producers down into three categories which are marginal producers, infra-marginal producers and extra-marginal producers. The marginal producers are the producers whose production costs equal to market price. Marginal producers will find that their productions are not worthwhile if the market price decreases.

On the other hand, the production cost for infra-producers is below the market price. This enables this kind of producers to put their price above their minimum worthwhile price and at the same time remain below the market price. As for extra-producers, the production cost for this kind of producers is above the market price. They will only find that their production is worthwhile when the market price increases. Hence, due to the different in production cost, the different producers of a commodity would have to adjust their amount of supply at different price thresholds. All these are summarized in Figure 19 as shown below.

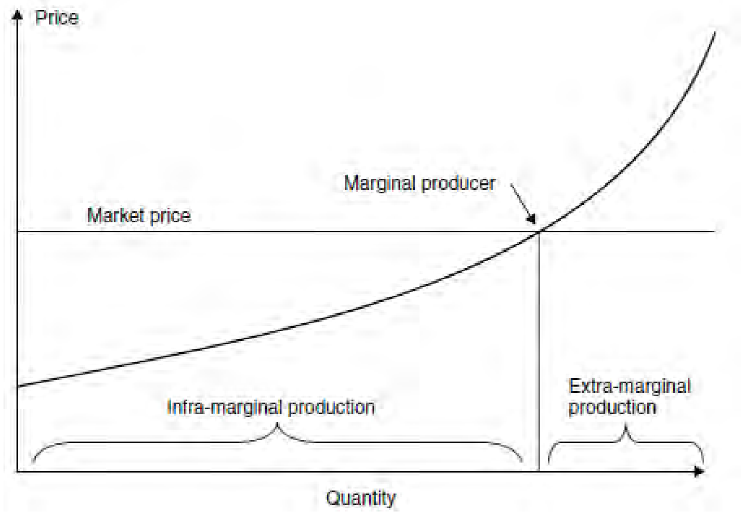


Figure 19: Type of Producers in respect to Market Price (Kirschen and Strbac, 2004)

As for the Elasticity of Supply, the rate of change of quantity of supply relative to the rate of change of market price is called Price Elasticity of Supply. The elasticity of supply is always positive and its value is normally higher in a long run since the suppliers have the opportunity to increase the means of production.

3.2.2.1 Changes in Supply

In constructing a supply curve, the price is the most significant influence on the quantity supplied of any product. But other factors can and do affect supply. The supply curve is drawn on the assumption that these other things are fixed and do not change. If one of them does change, a change in supply will occur, meaning that the entire supply curve will shift.

“The basic determinants of supply are (1) resource prices, (2) technology, (3) taxes and subsidies, (4) prices of other goods, (5) expected price, and (6) the number of sellers in the market. A change in any one or more of these determinants of supply, or supply shifters, will move the supply curve for a product either right or left" (McConnell Brief).

A shift to the right, as from S1 to S2 in Figure 20, signifies an increase in supply: Producers supply larger quantities of the product at each possible price. A shift to the left, as from S1 to S3, indicates a decrease in supply: Producers offer less output at each price.

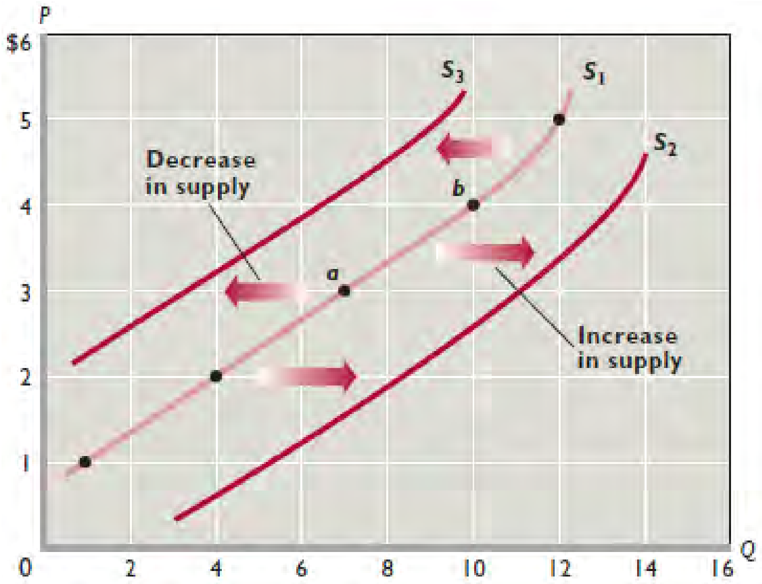


Figure 20: Changes in Supply (McConnell Brief)

3.2.3 Market Equilibrium

In the competitive electricity market large numbers of producers compete with each other to satisfy the wants and needs of a large number of consumers. Consumers help balance supply and demand, and ensure reliability by modifying the way they use and purchase a commodity. Customers have demands that are sensitive to price, and higher prices produce lower demands. In this way, we reach a point where the quantity demanded by consumers at current price will equal the quantity supplied by producers. So in a competitive market, a market is said to be in equilibrium state when the quantity that the suppliers are willing to provide is equal to the quantity (q) that the consumers wish to obtain. Market equilibrium happens at equilibrium price or market clearing price (π*).

The market equilibrium can be illustrated using the demand curve and supply curve as shown in Figure 21. In this situation, the quantity of a commodity and the market price will settle at the intersection of these two curves.

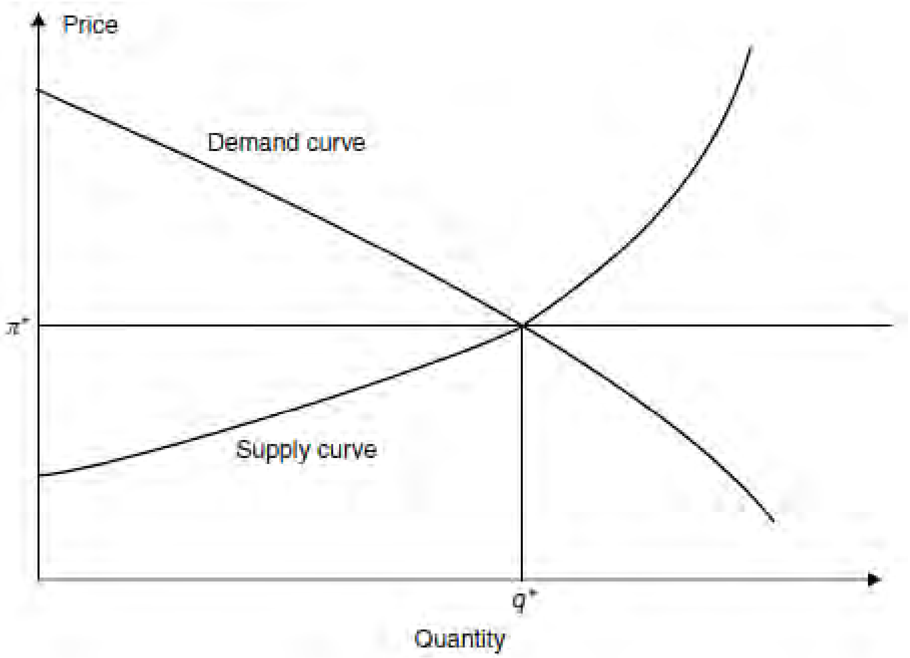


Figure 21: Market Equilibrium (Kirschen and Strbac, 2004)

When a competitive market is allowed to operate freely, the resulted equilibrium price will push the consumers' surplus and producers' profit to the maximum level. However should external interventions take place, this will prevent the price from settling at equilibrium price and hence the surplus and profits are not maximized. Figure 22 below shows the consequences when a commodity price settles higher or lower than the equilibrium price.

Consumers' surplus is defined as the difference between the price that a consumer is willing to pay and the actual price that they pay.

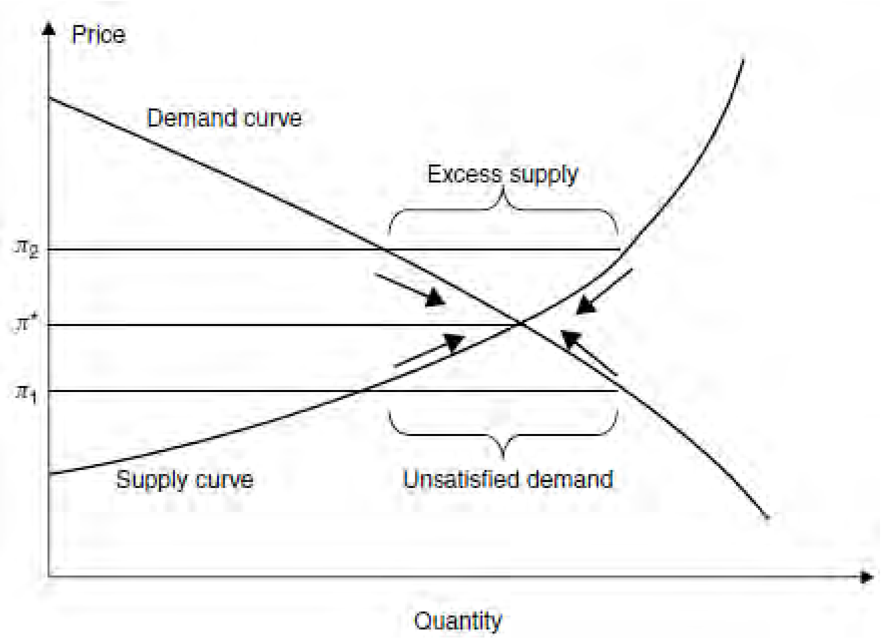


Figure 22: Stability of the market equilibrium (Kirschen and Strbac, 2004)

If the market price settles higher than the equilibrium price, the demand will reduce, this in turn leaves the producers with excess supply. In this situation, the producers will normally reduce their production so that the amount of commodities that they are willing to sell is equal to the amount that the consumers are willing to buy.

On the other hand, if the market price is lower than the equilibrium price, only limited number of producers will find that the price is worthwhile to produce goods. This will reduce the availability of supply in the market (shortage or excess demand) which leaves some amount of demand unsatisfied. Hence, in a competitive market, market price that is equal to the equilibrium price will basically help to give full advantage to both the producers and the consumers.

3.3 Changes in Demand, Supply and Equilibrium

3.3.1 Changes in Demand

If supply of some good is constant and the demand for the good increases (Figure 23 below), as a result, the new intersection of the supply and demand curves is at higher values on both the price and the quantity axes. Clearly, an increase in demand raises both equilibrium price and equilibrium quantity. Conversely, a decrease in demand (Figure 24 below), reduces both equilibrium price and equilibrium quantity.

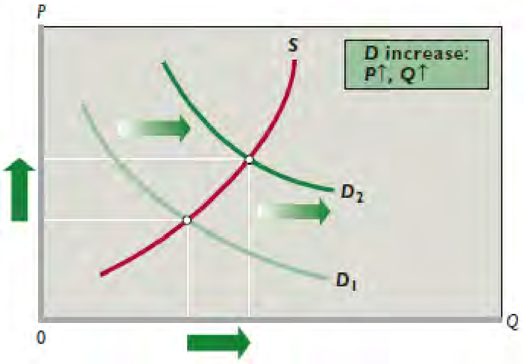


Figure 23: Increase in Demand
Source: (McConnell Brief)

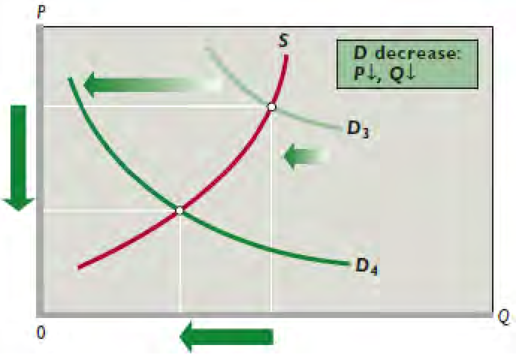


Figure 24: Decrease in Demand

3.3.2 Changes in Supply

If the demand for some good is constant but the supply increases (Figure 25 below), the new intersection of supply and demand is located at a lower equilibrium price but at a higher equilibrium quantity. An increase in supply reduces equilibrium price but increases equilibrium quantity. In contrast, if supply decreases (Figure 26), equilibrium price rises while equilibrium quantity declines.

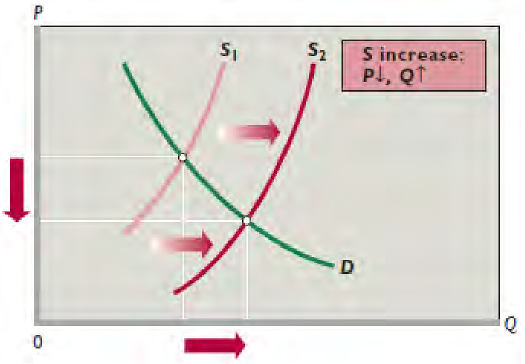


Figure 25: Increase in Supply
Source: (McConnell Brief)

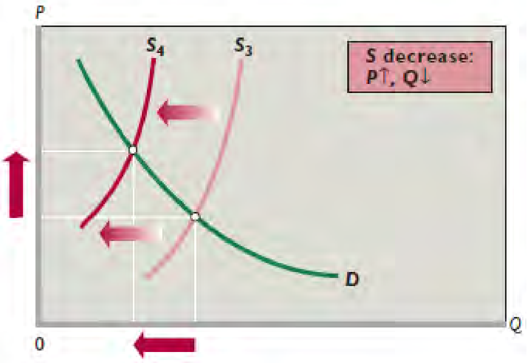


Figure 26: Decrease in Supply

As we see in Figures 23-26, Changes in demand and supply and the effects on price and quantity. The increase in demand from D1 to D2 in (Figure 23) increases both equilibrium price and equilibrium quantity. The decrease in demand from D3 to D4 in (Figure 24) decreases both equilibrium price and equilibrium quantity. The increase in supply from S1 to S2 in (Figure 25) decreases equilibrium price and increases equilibrium quantity. The decrease in supply from S3 to S4 in (Figure 26) increases equilibrium price and decreases equilibrium quantity. The upward arrows in the boxes signify increases in equilibrium price (P) and equilibrium quantity (Q). The downward arrows signify decreases in these items.

3.4 Complex Cases

When both supply and demand change, the effect is a combination of the individual effects.

3.4.1 Supply Increase and Demand Decrease

A supply increase for some good and a demand decrease will affect the equilibrium price. Both changes decrease price, so the net result is a price drop greater than that resulting from either change alone. But in the case of equilibrium quantity the effects of the changes in supply and demand are opposed. The increase in supply increases equilibrium quantity, but the decrease in demand reduces it. The direction of the change in equilibrium quantity depends on the relative sizes of the changes in supply and demand. If the increase in supply is larger than the decrease in demand, the equilibrium quantity will increase. But if the decrease in demand is greater than the increase in supply, the equilibrium quantity will decrease.

3.4.2 Supply Decrease and Demand Increase

A decrease in supply and an increase in demand for some good both increase price. Their combined effect is an increase in equilibrium price greater than that caused by either change separately. But their effect on the equilibrium quantity is again indeterminate, depending on the relative sizes of the changes in supply and demand. If the decrease in supply is larger than the increase in demand, the equilibrium quantity will decrease. In contrast, if the increase in demand is greater than the decrease in supply, the equilibrium quantity will increase.

3.4.3 Supply Increase and Demand Increase

If supply and demand both increase for some good the effects are opposed. A supply increase drops equilibrium price, while a demand increase boosts it. If the increase in supply is greater than the increase in demand, the equilibrium price will fall. If the opposite holds, the equilibrium price will rise. If the two changes are equal and cancel out, price will not change. The effect on equilibrium quantity is certain. The increases in supply and in demand both raise the equilibrium quantity. Therefore, the equilibrium quantity will increase by an amount greater than that caused by either change alone.

3.4.4 Supply Decrease and Demand Decrease

And the last case is about decreases in both supply and demand for some good. If the decrease in supply is greater than the decrease in demand, equilibrium price will rise. If the reverse is true, equilibrium price will fall. If the two changes are of the same size and cancel out, price will not change. Because the decreases in supply and demand both reduce equilibrium quantity, we can be sure that equilibrium quantity will fall.

3.5 Types of markets

The previous section has described and concluded that a market is a mechanism for matching supply and demand of a commodity through an equilibrium price. In addition to that, there are a few types of markets that serve different purposes of trading.

The types of markets are determined by following matters:

- The date of delivery of the commodities
- The mode of settlement
- Conditions that might be attached to the transaction

The way the buyers and sellers settle those matters will define the type of market that they involve in. Each type of market will be discussed in the following subsections.

3.5.1 Spot Market

In a spot market, seller delivers the goods immediately and the buyer pays on the spot. This type of market is very straight forward whereby there is no condition attached to it. Spot market has the advantage of immediacy. The sellers can sell the amount that they have available while for the consumers, they can purchase the exact amount that they need.

However, in a spot market, the price of the goods tends to change quickly. It is very much influenced by the demand and supply. The price will easily go up when the demand exceeds the available supply and vice versa. A sudden increase in demand (or a drop in production) sends the price soaring because the stock of goods available for immediate delivery may be limited. Similarly, a glut in production or a dip in demand depresses the price. The price in the spot market is also affected by the speculations and news about the future availability of a commodity. The unpredictable price of goods in spot market makes life harder for the traders as they are exposed to various risks.

Another type of market is needed by this kind of traders in order to protect them from those risks especially. Forward markets, future markets and a few others are quite useful for the traders to get their interest protected.

3.5.2 Forward Contract and Forward Markets

If in the future, the sellers or producers do not want to risk their goods to be sold at a lower price while the buyers at the same time don’t want to bear the risk of buying at high price, these sellers and buyers can “lock in” in the price by signing a forward contract.

A forward contract specifies the following matters:

- quantity and quality of the commodities to be delivered
- date of delivery
- date of payment following delivery
- penalties if fail to meet the commitment
- the price to be paid

The agreed price is based on their estimate of spot price at the delivery time. However, if at the delivery time, the spot price is higher than the agreed price, the forward contract will present a loss to the seller because they cannot sell their good at higher price while the buyer can enjoy the surplus as they pay a price which is lower than the spot price.

On the other hand, if the spot price is lower than the agreed price, the buyers will take turn to be at loss as they have to buy the goods at a price higher than the spot price. This time around, the sellers will gain profit out of the forward contract.

"If enough sellers and buyers are interested in signing forward contracts of a commodity, then a forward market for that commodity will develop. This forward market opens up a larger number of possible trading partners which in a way helps to determine whether the price that is being offered is reasonable or not" (Kirschen and Strbac, 2004).

In some cases, at some points, two parties may want to negotiate all the details of a forward contract. This is the case when the contract is to cover the delivery of a large quantity over a long period of time or if special need to be discussed. This kind of negotiation somehow is very expensive that lead the parties to use standardized terms and conditions.

This standardization makes possible the resale of future contract. For example, if a company realizes that it will not need all the commodity for which it has signed forward contracts, rather than wait until the contracted date of delivery to sell the excess commodity on the spot market, it can resell the forward contracts it holds to other companies. On the other hand producers who have signed contracts may realize that they have overestimated the quantity that they will be able to produce. If they cannot deliver the quantities specified in the contracts, they will have to cover the deficit by buying the commodity on the spot market. Rather than hope that the spot price will be favorable on the date of delivery, these producers could buy the forward contract from a company which sell its contract to offset their anticipated deficit. The price at which forward contracts are traded will be the current market price for forward contracts with the same delivery date. Depending on the market's view of the evolution of the spot price, this resale price may be higher or lower than the price agreed by the originators of the contract. This secondary market helps the parties to manage their price risk (or their exposure to fluctuations in the spot price) and at the same time conform to the conditions of the contract (Kirschen and Strbac, 2004).

3.5.3 Future Contracts and Future Markets

A contract is called a future contract when it does not involve physical delivery which means there are parties that buy a contract for delivery in the future with the intention to sell it later at a higher price. From another perspective, this can be seen as parties that sell a contract first with hope to get a new one at a lower price. The parties that buy and sell the future contracts are called speculators. According to Kirschen and Strbac, as the date of delivery approaches, the speculators must balance their position because they cannot produce, consume or store the commodity.

In spot markets, producers and buyers are exposed to some other risks other than price risk. Hence, with the existence of speculators in future market they prefer to transfer the price risk by paying the speculator to take care of this additional risk. As for the speculators, they can easily offset the losses in the future market as speculators normally have good financial position. Furthermore, speculators do not restrict themselves to one commodity but they involve in future contracts of other commodities as well which in a way reduce their exposure to any possible risks.

The market as a whole benefits from the participation of speculators even though sometimes they make a lot of profit from their trades. This is because the participation of speculators increases the diversity of the market participants. This makes physical participants (those who produce or consume the commodity) to find their counterparties for their trades more easily and hence increase the liquidity of the market. The increase in liquidity may help the market to discover the price of a commodity (Kirschen and Strbac, 2004).

3.5.4 Options

Futures and forwards contracts are firm contracts in the sense that delivery is unconditional. Any seller who is unable to deliver the quantity agreed must buy the missing amount on the spot market. Similarly, any buyer who cannot take full delivery must sell the excess on the spot market. In other words, imbalances are liquidated at the spot price on the date of delivery.

Unlike forward and future contract, options are contracts that come with a conditional delivery and this condition will only be exercised if the holder feels that it is worthwhile to do so. They are two varieties of options which are calls options and puts options.

A call option gives the holder (consumer) the right to buy a given amount of commodity at a price, which called exercise price, in a future date. On the other hand, a put option is the right for the holder (producer) to sell a given amount of commodity at the exercise price in a future date.

The exercise of the rights is very much depends on the spot market price of a commodity. If an exercise price of a call option is lower than the spot market price, then the holder (consumer) will find it worthwhile to have the option exercised. However, if the exercise price is higher, the holder (consumer) has the right not to exercise the option and they can get the goods from the spot market instead. Same goes to put option whereby the holder (producer) can choose not to exercise the option if the exercise price is lower than the spot market price. On the other hand, the holder (producer) will definitely exercise their right if the exercise price is higher than the spot market price.

Hence, buying an option contract can therefore be considered as a way for the holder (consumer or producer) of the contract to protect itself against the risk of having to trade the commodity at a price less favorable than the spot market (Kirschen and Strbac, 2004).

3.5.5 Contracts for Difference

In some cases, sometimes the price of a commodity is controlled by a centralized market. This gives the traders no option of making use of forward market, future market or options to reduce their risks. In this case, contracts for difference can be used whereby the parties will agree on the amount of the commodity and also a price which is called strike price.

After the agreement has been made, the parties will enter the centralized market like other participants do. Once the trading on the centralized market is completed, the contract of difference is settled as follows.

If the strike price is lower than the centralized market price, the buyers will pay the sellers the difference between the strike price and the market price times the amount of the commodity agreed in the contract.

If the strike price is higher than the centralized market price, the sellers will pay the buyers the difference between these two prices times the amount of the commodity agreed in the contract.

In general, contracts for difference are a combination of a call option and a put option with the same exercise price which is applied in a centralized market. From all the market types described above, the spot market price appears as an indicator that drives all prices in other markets. This is because the spot market is the last resort where all the parties will refer if any imbalances occur in any of the markets. Hence, the spot market plays a fairly important role in matching the supply and demand.

3.6 Characteristics of electricity markets

When applying economic theory to electricity markets there are two major difficulties concerning the nature of demand and supply. Firstly, elasticity of demand is very low if not zero. Secondly, the characteristics of supply costs in electricity markets are not compatible with the assumptions made in competitive economics, as we so them before when analyzing the market equilibrium. We will see how supply and demand are usually presented in electricity markets and their main characteristics.

3.6.1 Supply

Supply in electricity markets is the combined output of all generators used to satisfy the consumer’s demand for electricity. As in any market, the supply curve shows the total amount offered for sale at any given price for any given period. In the short term electricity supply is considered to be fixed. In the long term the production capacity may be changed (Boisseleau, 2004).

When an electricity market is defined, the total electricity supply is usually represented by a merit order curve. Such curves range from the least expensive to the most expensive units. We can see in figure 27 the representation of a supply curve. The merit order curve presents the costs and capacities of all generators. There are many differences between costs. Usually the differences between production costs occur because of the different technologies that are being used, related to the fuel. For example, hydropower plants usually have lower marginal costs than gas powered plants.

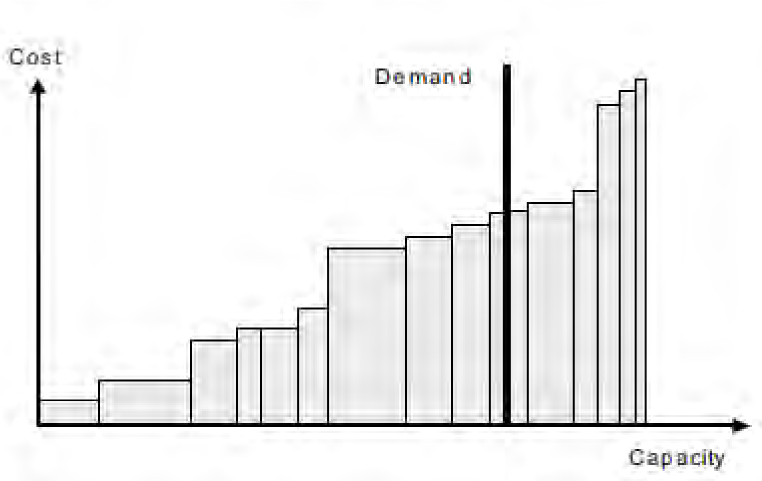


Figure 27: Merit order curve, (Boisseleau, 2004)

There are three main characteristics of electricity supply that must be considered. Different cost levels, non-convexity of generator costs and concentrated structure of the market.

"In a single power plant, the characteristics of supply are not compatible with assumptions of competitive economics because production costs are not convex. Convex costs have the property that twice as much output always costs at least twice as much to produce (Stoft, 2002). Electricity production costs are not convex due mainly to the existence of startup costs and no-load-costs" (Boisseleau, 2004).

"For instance, if the startup cost of a plant is 20 Euro/MWh and if its marginal cost is 25, producing one MWh over two hours would cost 70 Euro/MWh while producing two MWh in the same period would only cost 120 Euro/MWh. Hence, producing twice as much is cheaper per unit. This characteristic is important when estimating the real cost of production in a competitive environment" (Boisseleau, 2004).

Finally, the number of sellers in many countries is still law today and that is an important problem for establishing a competitive market. This is because the past years electricity industry was organized as a monopoly and in many countries most power plants are still owned by a small number of producers. This market structure is an important barrier in the creation of competitive electricity markets.

3.6.2 Demand

Demand in electricity markets as the quantity of electricity that end-users are willing to consume at any given price. Electricity demand has three important features: seasonal variations, segmentation of consumers and low elasticity.

We can see an example in Figure 28 of seasonable variations of electricity consumption in France in 2001.

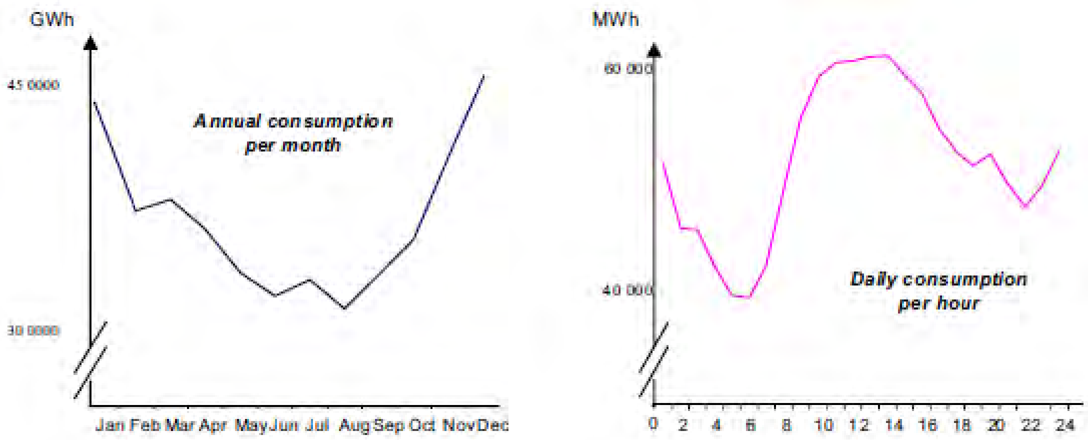


Figure 28: The seasonable variations of electricity consumption in France 2001 (Boisseleau, 2004)

Also we can summarize (see Figure 29) the seasonal variations in demand in a load curve which plots demand against duration. Such a curve can be constructed for different time scales and areas (Boisseleau, 2004).

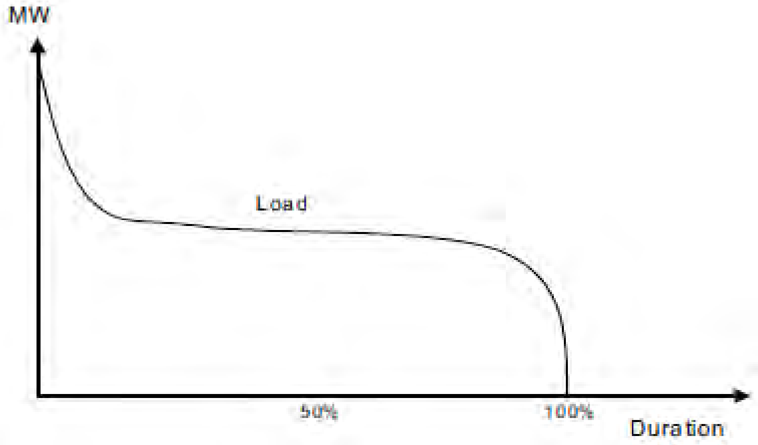


Figure 29: Load duration curve (Boisseleau, 2004)

The demand of electricity varies widely between peak time (day) and off peak time (night) and seasons (winter/summer). This variation is simply due to the fact that most companies and households do not consume electricity during the night. Very high peaks of demand occur during very hot or very cold weekdays when everyone is using air conditioning or electric heating. The lowest levels of demand for electricity occur in the middle of the night.

Demand, according to Boisseleau (2004) can be divided into several segments according to the level of need and sensitivity to price change of its buyers. “Different categories can be defined to improve the transparency of electricity prices charged to industrial end-users and domestic consumers. Domestic consumers and industrial consumers are broken down into three categories according to their level of electricity consumption: small, medium and large consumers” (Boisseleau, 2004).

Lastly, the elasticity of demand is a sensitive issue in electricity markets. As in any market, the elasticity of demand represents how consumers react in a change in price, in this case electricity prices. In electricity markets elasticity of demand is very low. There are not many alternatives for the consumers and also electricity is a product which is very important for the consumers.

4. Design of a competitive electricity market

4.1 Introduction

One of the aims behind the restructuring of the electricity industry was to allow market forces to play a greater role in the operation and planning of power systems. The basic expectations of such a change were that efficiency would increase and that electricity prices would decline without compromising reliability (Kockar, 2003).

“Electricity market restructuring emphasizes the potential for competition in generation and retail services, with operation of distribution and transmission wires as a monopoly” (Hogan, 1998).

The traditional electricity system is separated into generation, transmission and distribution. But this separation is insufficient. The first step for restructuring the electricity market emphasizes the unbundling of the traditional vertical integrated utilities into separate commercial units that operate independently of each other. These commercial units - generation, transmission and distribution – will operate independently and the security of the system operation will be handled by an independent entity which is called system operator (S.O.). The economic operation of a power system is managed by a market operator responsible for balancing supply and demand and for setting prices.

4.2 Electricity market design

4.2.1 Three levels of market design

When introducing competition in the electricity sector we must define which activity should be organized based on market mechanisms and competition and which activity should stay a monopoly and be regulated (Boisseleau, 2004).

Three levels of market design can be identified according to Boisseleau (Figure 30). The first level refers to market design as the whole value chain of the electricity industry from generation to final load, including both wholesale and retail electricity markets. In the second level, authors like Hogan (1998) refer only to the wholesale market and includes short-term spot markets, bilateral transactions, transmission congestion contracts, networks access charges and more. And finally in the third level, there are authors refer to market design as the detailed functioning of a marketplace such as the type of auction, the format of bids and the rules governing the marketplace (Boisseleau, 2004).

The second type of market restructuring - the wholesale market design as explained by Hogan - it is going to be analyzed later in this chapter.

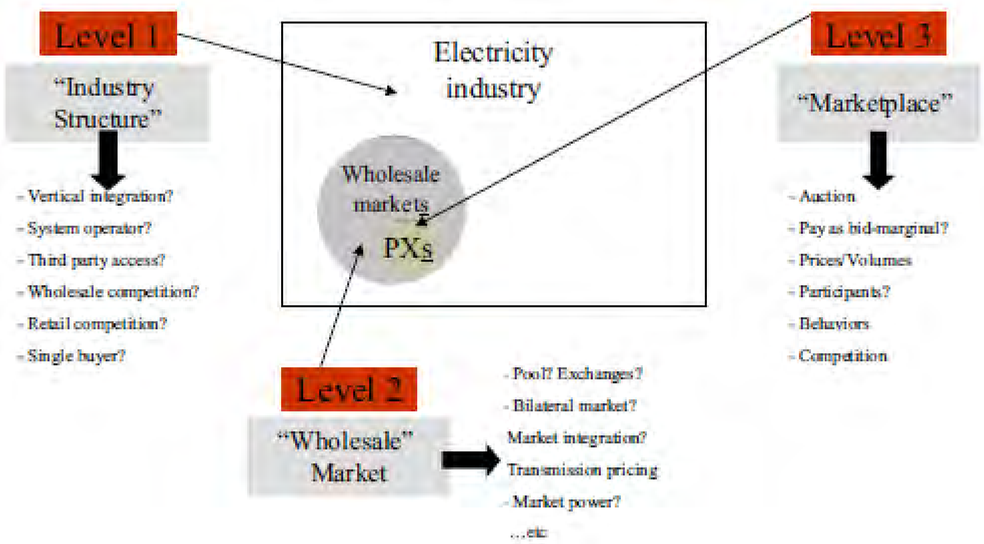


Figure 30: Three levels of market design (Boisseleau, 2004)

As we said in the previous chapter, markets exist wherever buyers and sellers interact to buy or sell a product at a mutually agreed price. The Oxford dictionary of Economics defines a market as "A place or institution in which buyers and sellers of a good or asset meet". However, the everyday sense of the word "market" also tends to include market participants, market conditions, legal framework, geographical area and more. But when we are talking about electricity markets the word "market" has a different meaning (Boisseleau, 2004).

"In electricity markets generators, traders, distribution companies are "markets participants" while regulators, and laws and legal aspects constitute, the "market's legal framework". Also, since power exchanges are markets for wholesale electricity, the retail market is excluded from our definition of a market. So, the word market will refer to all places or institutions in which buyers and sellers of wholesale electricity contracts meet to ratify" (Boisseleau, 2004).

So as generation companies and load supplying companies became market participants, they are looking to sell or buy electricity. Also other market players appeared, like traders who buy and sell electricity.

It is being attempted the restructuring of electricity market to resemble traditional markets of other goods. "However electricity defers from other commodities in a number of significant ways:

- The need to instantaneously balance generation and demand,
- No means to effectively store large amounts of electricity,
- Transmission being a natural monopoly,
- Severe limitations in the ability to control the flow of electricity" (Kockar, 2003).

These factors make electricity markets more complex to run and it is needed a good central coordination. The first feature requires real-time balancing between generation and demand at every bus. The lack of storage means that prices are more volatile and sensitive to market power, which means that some participants are in a position to influence the market outcome, and thus benefit at the expense of others.

Another feature that influences electricity markets to be perfect competitive is that transmission is a natural monopoly and it is very difficult to control effectively the flows of electricity. This special characteristic is not appeared in most traditional markets. This is a significant problem in electricity markets, because if the control of transmission flows is inadequate then there can be as system failure because of unreliable operation (Kockar, 2003).

All these special features of electricity markets will be considered when it will be presented later, how a competitive electricity market is structured.

4.3 Wholesale competitive electricity market design

Wholesale market design is central to the introduction of competition in the electricity industry. "A short term electricity market coordinated by a system operator provides a foundation for a competitive electricity market. Combined with long term contracts for generation and transmission congestion, the spot market and competitive market pricing can support open access to the transmission grid" (Hogan, 1998).

Coordination through the system operator is unavoidable. Beginning with the establishment of a bid-based short run electricity market we create the basis in the wholesale electricity market for competition among the market participants. Next it is going to be analyzed how transmission costs change the locational prices of electricity. Then long-run market contracts are introduced in order to mitigate or share the risk of volatile market prices. And lastly, scheduling and balancing operations from the system operator will define the final market price.

4.3.1 Economics of a competitive electricity market

As we said earlier, the first step for restructuring the electricity market emphasizes the unbundling of the traditional vertical integrated utilities into separate commercial units that operate independently of each other. Generation, transmission and distribution will operate independently and the security of the system operation will be handled by an independent entity which is called system operator (S.O.). A pool-based market coordinated by a system operator is the one which help as to re-build the electricity market (Figure 31).

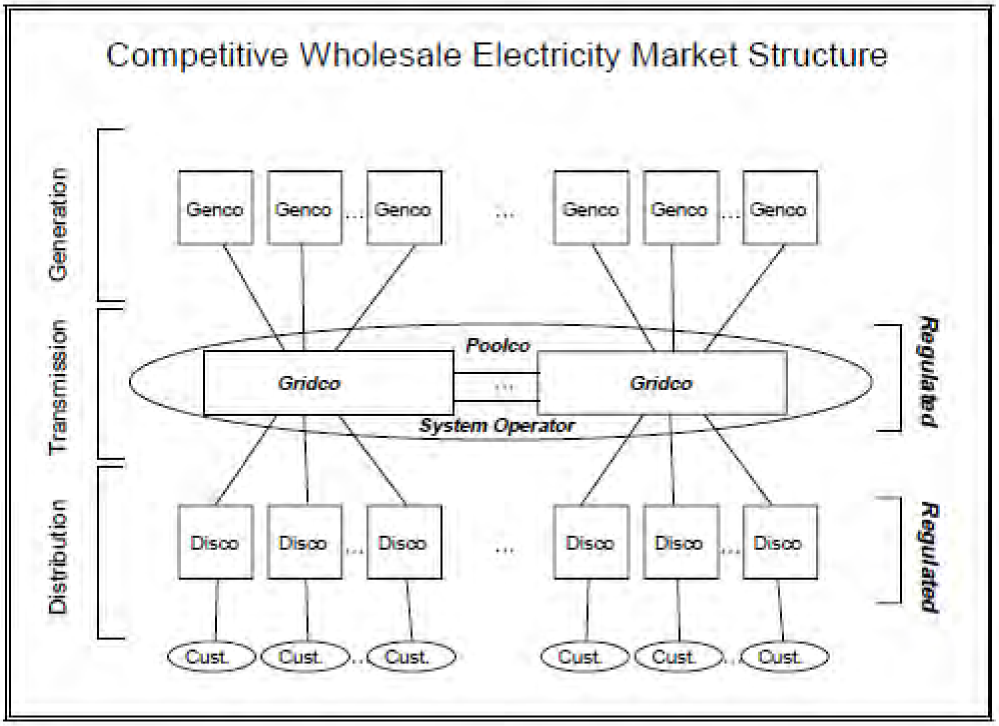


Figure 31: Competitive Wholesale Electricity Market Structure (Hogan, 1998)

One of the most significant requirements and simultaneously a constraint is the reliability of the system operation. The current electricity networks are complex. Electricity flows freely in the transmission grid and the use of the system operator which coordinates the transmission has a central role (Hogan, 1998).

The flow of electricity in the system is maintained and controlled by dispatch centers. It is the responsibility of the dispatch center to match the supply of electricity with the demand. So control of the transmission usage by the system operator means control of dispatch.

As, we earlier said, the system operator should be independent of the electric utilities and the other market participants. So the role of the system operator is to control the procedure and not to participate in it and compete in the energy market (Hogan, 1998).

Under the competitive market assumption, producers are no longer these who determine the market price. Producers are price takers and consumers are those who determine the market price they are called price makers.

4.3.2 Short-run market

The basis for building a competitive wholesale electricity market is the short run market. The short run is a short time for the human and in most cases is fifteen minutes or half an hour. In the short-run we assume that there is no congestion cost and transmission of real power flows freely to the grid. All market participants, power plants, transmission grid and distribution lines are all in place (Hogan, 1998).

In the short-run market electricity power is a commodity product and the decision that should be taken from the system operator is about the delivery of power. The operation of the market is about delivering power from generators to consumers. In a half hour the market participants compete to each other to move real power from producers to consumers.

As we earlier said, in the competitive electricity market consumers are price makers and generators are price takers. Consumers decide in what price they are willing to buy power and generators are bidding and compete to each other in order to being “dispatched” and produce power that is needed.

More precisely, power plants have marginal costs of generating real power and consumers have different quantities of demand. The consumers’ demands are depending on the price at that half hour. Consumers have demands sensitive to prices, that’s why higher prices produce lower demands.

Marginal costs stack up to define the generation short-run marginal-cost curve (Figure 32), from least to most expensive, which is about power supply (Hogan, 1998).

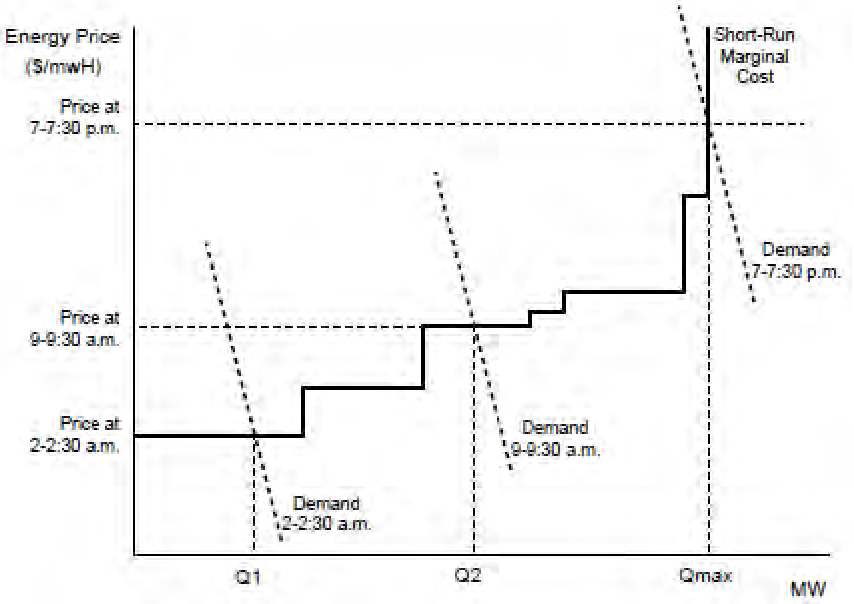


Figure 32: Short-run marginal-cost curve (Hogan, 1998)

Generators and customers do not act unilaterally. They provide information to the dispatcher. The result of the decision process is what power plants will run at the half hour. The system operator’s target is to match supply and demand in the most efficient way based on the participants’ bids. So the outcome of system operator’s decision is a least-cost dispatch which simultaneously is the competitive-market dispatch.

4.3.2.1 Differences between traditional power pool and competitive market

In the traditional power pool the power that the customer buys from a generator is based according to an average cost. Typically the cost data come from engineering estimates of how is the cost of a power plant at a given time in order to produce energy. However based only to these costs it is problematic because the true opportunity cost of this operation may be different. Opportunity cost is based on the decision of the generator that may find it worthwhile not to produce energy in a specific cost – because the generator may include other features in his decision which may change the operation cost. For instance, the producer may find it worthwhile not to produce electricity in a specific half hour but buy power from the pool and sell it. Or the producer may find it worthwhile not to operate at all for the specific half hour.

“The alternative of the traditional model is replacing the engineering estimates with market bids. Each bid defines the minimum acceptable price that the generator would accept to run the power plant at a given half hour” (Hogan, 1998).

Lastly, the operation of bidding by the generators is not a simple procedure. The true marginal cost for each generator is the optimal bid. If a generator bids more, then in the competitive electricity market there is enough competition that lessens the chance of the generator to being dispatched. That means that if the generator is bidding more probably he won't be selected to run his power plant. On the other hand, if the generator bids less then there is a significant risk to run the power plant in a cost smaller that the cost of the generation.

The premise for this operation to be successful is that there is no collusion. To summarize the procedure, the system operator takes bids from buyers and sellers and balance supply and demand at the given half hour. This balancing maximizes the benefits for producers and consumers. The market price that finally occurs, it is called "market equilibrium price" and every half hour consumers pay producers the equilibrium price (Hogan, 1998).

4.3.3 Transmission Congestion

In the short-run market we assumed that power plants, transmission grid and distribution lines are all in place and that transmission was nothing more than putting power into one part of the grid and taking it out at another.

However, not all power is generated and consumed at the same location. In reality generating plants and customers are connected through a free flowing grid of transmission and distribution lines. The transmission complicates the short-run market through the introduction of losses and possible congestion costs (Hogan, 1998).

Losses are easy to be handled. A generator may produce power in a location and deliver it far away in different locations. That delivering of power creates losses, so the marginal cost of delivering power to different locations defers at least by the marginal effects on losses by the system. But this additional effect does not complicate the short-run market. The equilibrium price that will occur would have taken into account the cost of losses and the result will be different prices according the location.

On the other hand transmission congestion is more complicated to be handled. The transmission grid has constrains, for example thermal constrains or voltage constrains. When delivering power from one location to another, the distance between these two locations may be long, the grid constrains will impose a higher marginal cost in these locations.

In the simplest case power will flow from the low cost to the high cost location. But because of the grids limitations in high demand periods not all power that could be generated in the low cost location could be delivered in the high cost location. In this case the low cost plant will not be used efficiently and more expensive plants would cover the high demand for energy. The difference between the marginal cost at the high cost location and the marginal cost at the low cost location is called congestion rental. For example, if there is a cheap coal plant in a location but due to transmission constrains cannot operate at all, and there is in another location an expensive oil plant that costs more than twice to run, then the congestion rental (i.e. the difference between the marginal costs) would be greater than the cost of energy at the coal plant (Hogan, 1998).

However, the grid is not as simple as in a case with a single line between two locations. In the real network there are loops that make it more complicated, but the result would be the same.

The extension of the transmission congestion costs in the short-run market has no difficulty. The only difference is that now the market has a different price for each location. Customers will bid and set the maximum price that they are willing to pay in their location. Generators also will bid as before, but the bid now is going to be the minimum acceptable price for each location. Generators and customers see a single price at their location for the half hour, and the prices vary over the half hours to reflect the changes of supply and demand. Now the economic dispatch will include different prices for each location that combine generation, losses and congestion costs. The system operator coordinates the dispatch and the result will be the optimal price which balances supply and demand (Hogan, 1998).

The way that the short-run competitive market, which includes the transmission congestion costs, works, can be extended in bilateral transactions. We can assume that if market participants want to schedule a transmission between two locations this is the same as the difference in price between these two locations as explained above. In addition this type of pricing can be extended in day ahead scheduling and more.

4.3.4 Long-run market contracts

The spot market price is volatile either there are congestion constrains either there are not. With the continuing changing of the supply and demand conditions generators and customers will see fluctuations in the short-run prices. These fluctuations are a risk both for producers and consumers. In order to mitigate this risk the market offers long-term contracts.

As it was presented in the previous chapter in the traditional types of commodity markets there is a type of contract that is called “contract of difference”. When the price of a commodity is controlled by a centralized market contracts for difference can be used whereby the parties will agree on the amount of the commodity and also a price which is called strike price (Kirschen and Strbac, 2004).

The basic assumption in the traditional market is that if a specific producer wants to satisfy the demand of a specific consumer, they make an agreement. But when the customer’s needs change then the customer might sell the contract of this agreement in the secondary market. The same applies to the producer.

The short-term pool based electricity market coordinated by a system operator is a centralized market. Generators provide power into the grid and consumers are taking power out of the grid. To achieve an efficient economic dispatch the dispatcher must have the freedom, in responding to the bids, to decide which plants run to generate the energy needed, independent of the long-term contracts. So, “short-term dispatch decisions by the system operator are made independent and without recognition of the long-term contracts” (Hogan, 1998). In this way electricity defers from other commodities.

Because of the very complicated grid interactions there is no possibility to identify which generator is serving which customer. The transmission constrains and the fact that there is no possibility to control flows, it changes the character of the long-term contracts. The contracts will provide a hedge, because of the volatility of the price, not by controlling the flow of power and which generator serves a specific customer, but with managing the flow of money. So in the competitive electricity markets the long-term contracts defer from the traditional markets because there is no need for any specific plant to deliver the commodity (i.e. real power) to any specific customer (Hogan, 1998).

4.3.4.1 First case: No transmission congestion and long-term contracts

In the first case we assume that there are no transmission congestion costs. So, there are no different prices in different locations and we can treat it like generation and consumption happen in the same location.

The contract for differences here has the role to mitigate the deviations from the equilibrium market price. We can assume that a producer and a consumer agree in a specific quantity for a specific price, for instance 100 MW for 5 cents. “On the half hour, if the pool price is 6 cents, the customer buys power from the pool at 6 cents and the generator sells power for 6 cents. Under the contract, the generator owes the customer 1 cent for each of the 100 MW over the half hour. In the reverse case, with the pool price at 3 cents, the customer pays 3 cents to the system operator, which in turn pays 3 cents to the generator, but now the customer owes the generator 2 cents for each of the 100 MW over the half hour” (Hogan, 1998).

But in this case of the short-term pool based electricity market there is a significant advantage comparing with the traditional spot market. In the traditional spot market, as we earlier said, the parties of the agreement may find it worthwhile to sell their contracts in the secondary market. In the competitive electricity market there is already a secondary market, because of the special structure of the market, which is the pool. So if the customer’s demand is above or below the agreed price of the contract, the extra power can be purchased or be sold at the pool price. Similarly for the generator, there is already a secondary market, the pool, for surplus or backup supplies. And if the customer consumes the agreed quantity and the producer generates the agreed quantity - as it has been agreed to the contract – then the market guarantees that the consumer will buy the agreed quantity from the producer at the agreed price, independently from the pool price at that half hour. So the long-run market contracts do not disturb the short-run market incentives and hence they can be used compatible with the short-run market (Hogan, 1998).

Finally, the system operator should not know the terms and conditions of the contracts between producers and consumers in order not to favor someone against another.

4.3.4.2 Second case: Transmission congestion and long term contracts

When transmission congestion is taking into account there are two problems that occur and that they should be handled. The first problem is different prices for each location because of the transmission constrains and monopoly of the system operator that can manipulate the dispatch and the grid expansion. When transmission congestions costs are added to the system, the revenues that are collected from customers exceed the payments to generators. This congestion rent itself will be high volatile with the same way as the short-run market prices. When the congestion rent is collected this payment goes to the system operator. So if the system operator keeps the congestion revenue, then there are incentives for the system operator to manipulate the dispatch and not let the grid expansion in order to have even greater congestion rentals. This is happening because as we earlier said the system operator is a natural monopoly (Hogan, 1998).

For the first problem the solution is a price hedge against the volatile locational congestion differentials. For the second problem the solution is removing for the system operator the possibility to keep the congestion rentals.

As it was described for the long-run market contracts for generation, in the same way it should be introduced long-run transmission congestion contracts, in order to mitigate the risk of fluctuations in the congestion rentals. Both types of contracts will operate simultaneously. As in the generation contracts, it is not possible for the system operator to know which generator delivers power to which customer. However, as in the generation contracts before, transmission congestion contracts would provide a compensation for differences in the congestion costs between different locations in the grid (Hogan, 1998).

In Figure 33, we can see an example of transmission congestion contracts which contain differences in locational prices due to transmission congestion costs and losses.

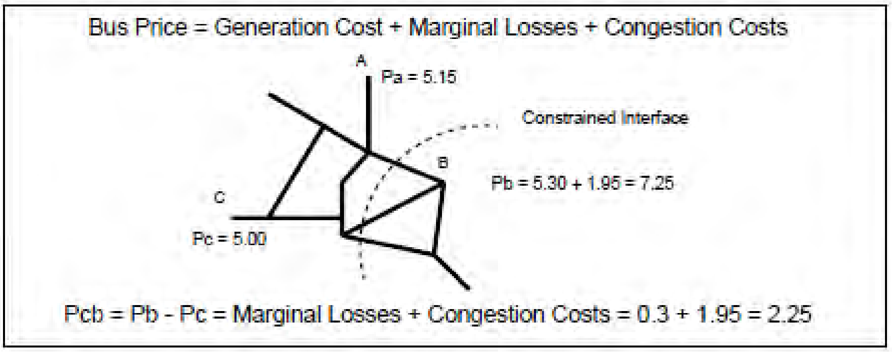


Figure 33: Network transmission congestion contracts (Hogan, 1998)

We can see in Figure 33, transmission between C and B would pay 2.25 cents. In this transmission charge the congestion cost is 1.95 cents and losses are 0.30 cents. The result of a transmission congestion contract between C and B would be a payment of 1.95 cents to the holder of the contract by the system operator. Hence, "if the participant actually transported the power, the transmission congestion contract would just balance the congestion charge for the quantity covered by the contract. And if the holder of the transmission congestion contract does not transport power, the result is the same as selling the transmission right to the actual user" (Hogan, 1998).

So the right provide by the contract would not be for specific movement of power but rather for payment of the congestion rental.

4.3.4.3 Transmission congestion contract auction and constrains with out of merit cost

In Figure 34 illustrates a hypothetical auction for transmission congestion contracts with two demand curves. As a network we get the simplest case, which is a network with three deferent locations.

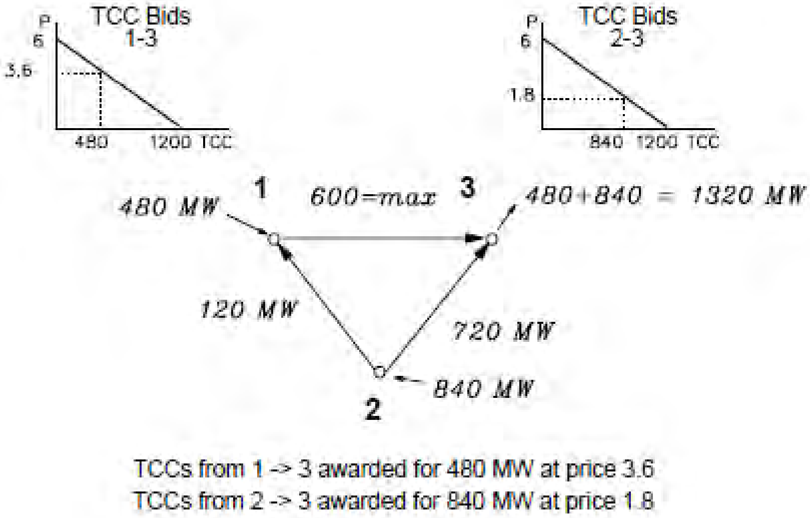


Figure 34: Auction of transmission congestion contracts (Hogan, 1998)

We can see in Figure 34 that the optimal price and quantity based on bids that maximizes the benefit for the contracts is 480 MW power at price 3.6 cents from bus 1 to bus 3 and 840 MW of power at price 1.8 from bus 2 to bus 3. These transmission congestion contracts will provide a price protection because of the volatility of the congestion costs.

In Figure 35 we can see the real power that will be produced and the prices in each of the three locations in a hypothetical short-run market.

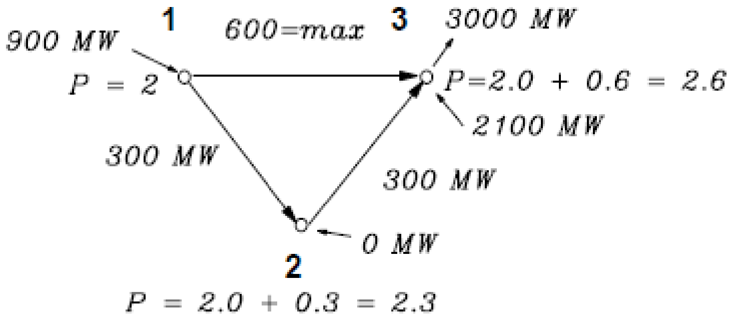


Figure 35: Constrains with out of merit costs (Hogan, 1998)

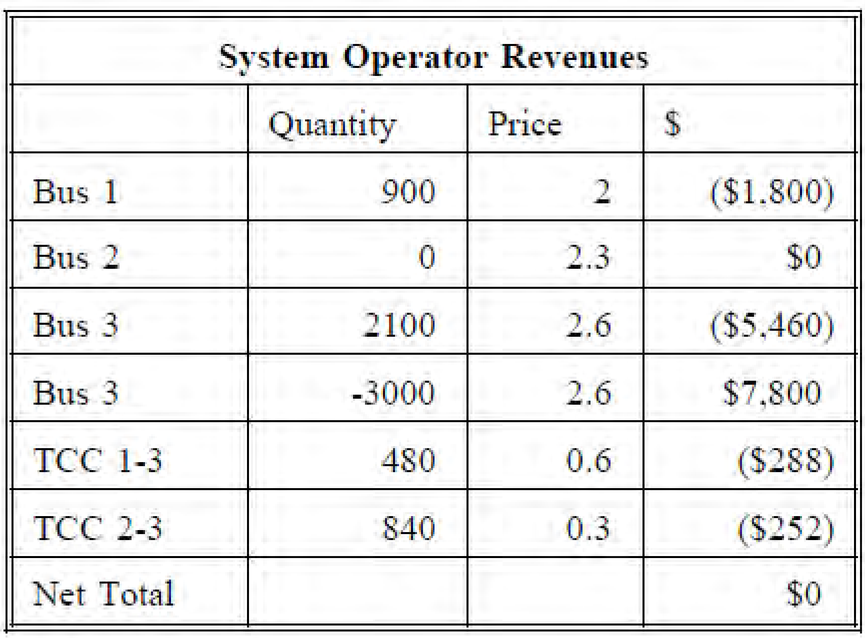
We can see that the total load on bus 3 is 3000 MW. The generation takes place at bus 3 is 2100 MW and the other 900 MW, in order to balance the supply and demand, come from bus 1. The market clearing prices are 2 cents at bus 1, 2.3 cents at bus 2 and 2.6 cents at bus 3.

We can see that the market equilibrium for this dispatch is different with the flows envisioned in the transmission congestions contracts in Figure 34, because as we earlier said the right provide by the contract is not for specific movement of power but for payment of the congestion rental.

“As long as the allocation of the transmission congestion contracts defines a set of inputs and outputs that would be simultaneously feasible, then the revenue collected from the spot prices for congestion will be sufficient to compensate the holders of the contracts for the obligations at the same set of spot prices” (Hogan, 1998).

Finally in Table 3 we can see the system operator revenues.

Table 3: System operator revenues (Hogan, 1998)



System Operator Revenues			
	Quantity	Price	$
Bus 1	900	2	($1,800)
Bus 2	0	2.3	$0
Bus 3	2100	2.6	($5,460)
Bus 3	-3000	2.6	$7,800
TCC 1-3	480	0.6	($288)
TCC 2-3	840	0.3	($252)
Net Total			$0

System operator collects the transmission congestion rents from the users of the system and distributes them to the holders of the contracts. In the example presented the payments exactly balance. In a more complicated network there probably will be an excess of congestion rents. This excess should not remain in the system operator but it will be shared according to a formula to those who paying the grid costs.

To sum up, "the system operator collects and pays according to the short-run marginal price at each location and it distributes the congestion rentals to the holders of the transmission congestion contracts". (Hogan, 1998)

4.3.5 Scheduling and balancing

The most attractive method in order to result the coordinated by the system operator short-run dispatch is day-ahead bidding. This does not require real-time dispatch capabilities and it is preferred because it provides a greater opportunity for participation by flexible demand.

In the day ahead bidding the system operator accepts bids for a scheduled dispatch a day ahead and determines the equilibrium price and any associated payment settlements (for example payments for transmission congestion contracts). (Hogan, 1998)

"This schedule then defines a set of commitments for delivering and taking power in the short-run dispatch. In the day-ahead event, the actual dispatch will differ from the scheduled commitments, and appropriate balancing settlements would be arranged" (Hogan, 1998). In Figure 36 it is presented a balancing price for deviations from scheduled commitments.

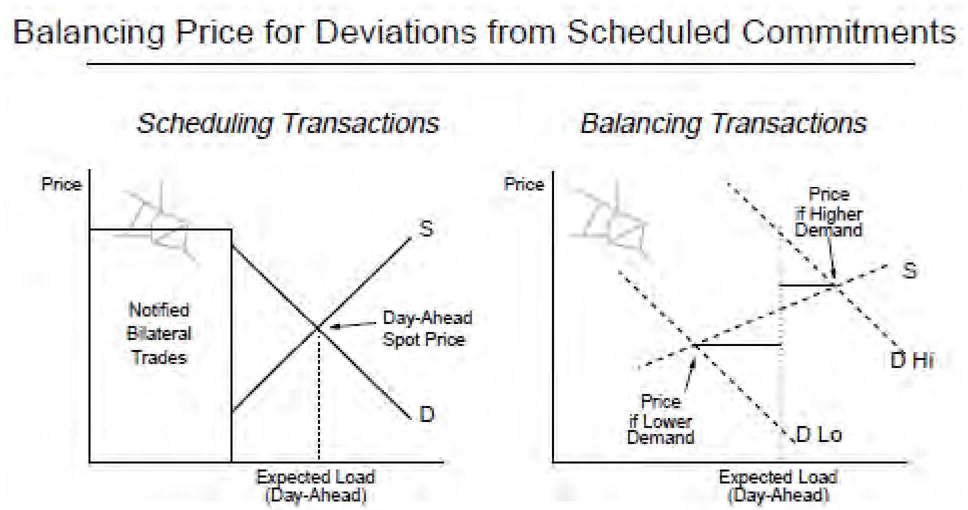


Figure 36: Balancing price for deviations from scheduled commitments (Hogan, 1998)

The way that day-ahead scheduling bidding works is that participants are bidding for supply and demand a day ahead. The system operator takes into account the day-ahead bidding and result a least-cost dispatch that matches scheduled demand and supply in the most optimal way, both for the producers and consumers.

The equilibrium price and the quantity that occur, define the day-ahead schedule. The system operator also defines reliability commitments in order to meet any expected deviations in the load from the day-ahead schedule. These commitments may include spinning and standby reserves (Hogan, 1998).

The schedule and the associated dispatch commitments would provide the reference point for the actual dispatch. Bids in the scheduling market could be revised to create balancing bids for increments and decrements against the dispatch commitments. Again the system operator would find the least-cost dispatch, hour by hour, based on the actual conditions and the final balancing bids. The result would be an actual dispatch with associated equilibrium prices and quantities. These prices and quantities would differ to a degree from the schedules (Hogan, 1998).

4.4 Case studies: The PJM and the Nordic Electricity Market approach

4.4.1 The PJM electricity market

“The PJM (Pennsylvania - New Jersey - Maryland) market is the largest centrally dispatched control area in North America and is often cited as one of the leading example of a successful competitive electricity market” (Boisseleau, 2004).

PJM provides an interesting example of market design where organized markets and transmission pricing are integrated and are at the heart of the functioning of the electricity market. PJM reaches into eight states and the District of Columbia in North America. It serves about 11 millions customers (Boisseleau, 2004).

PJM combines the power exchange and the system operator. It started operation of its spot market in 1997. At that time the spot market provided a single price for the entire PJM region. In situation of congestion, some generators were constrained on, while others were constrained off, which means that low cost plants will not be used efficiently and more expensive plants would cover the high demand for energy. The main drawback of this method was that generators constrained off were paid nothing, even though they had bids below the system price. The high cost that appeared by using more expensive generation was socialized into a charge applied to all loads (Boisseleau, 2004).

The single price was problematic as it was unable to reflect adequately locational value of energy throughout the market related to transmission constraints. For this reason PJM switched from a single price system to a locational marginal pricing. Since 1998, PJM has determined hourly locational marginal prices on a nodal basis which reflects the underlying cost of the energy and the marginal cost of transmission congestion.

In addition, PJM collects bilateral schedules and bids from market participants. Based on these schedules and bids, PJM determines an optimal dispatch for power flows and the associated locational marginal prices.

In order to allow financial hedging against price differences between locations, the locational marginal prices system as explained before in the wholesale analysis is accompanied by a system of transmission rights. These transmission congestion contracts compensate the holders of the contracts because of the congestion charges that arise from locational differences, as analyzed before.

The example of PJM is really interesting because it first worked with single zonal pricing and collapsed due to transmission constraints. Then PJM adopted a nodal pricing system, which appeared to be the most efficient approach, providing successful outcomes. PJM's successful experience with nodal pricing system shows the practical feasibility of such a system (Boisseleau, 2004).

4.4.2 The Nordic Electricity Market – A successful retail competitive market approach

The Nordic electricity market design is a very successful example of a competitive retail electricity market. It consists of five Nordic countries Norway, Sweden, Finland and Denmark. They present a very interesting example of how a power exchange is used for dealing with congestion. The wholesale market restructure as presented by

Hogan is the difficult part of restructuring the electricity market, and it provides the basis for building a competitive retail services upon it.

The Nordic electricity market is divided into regulated monopoly operations, transmission and distribution, and to competitive operations, generation and supply. On the regulated side, high voltage electricity transmission from production plants to distribution networks is controlled by transmission system operators (TSO). In the Nordic countries, each country has one legally separated transmission system operator. Low voltage distribution to end consumers is controlled by distribution system operators (DSO). There are large amount of DSOs in each Nordic country and most of them are small, municipally owned utilities (Tuovinen, 2009).

Competitive part of the electricity market is formed by two types of markets, the Nordic wholesale market and the national retail markets. On a Nordic wholesale market, electricity is produced in production plants under competition. The wholesale price is formed by the equilibrium of demand and supply in the Nordic power exchange (Nord Pool). Nord Pool consists of two markets, the physical market, Nord Pool Spot AS (which consists of day-ahead market Elspot and intra-day market Elbas), and financial market, Nord Pool ASA. Retailers buy their power from Nord Pool. They use bilateral contracts or produce their electricity themselves and sell it to the end consumers (Tuovinen, 2009). The structure of the Nordic electricity market, before and after the restructuring, is presented in Figure 37.

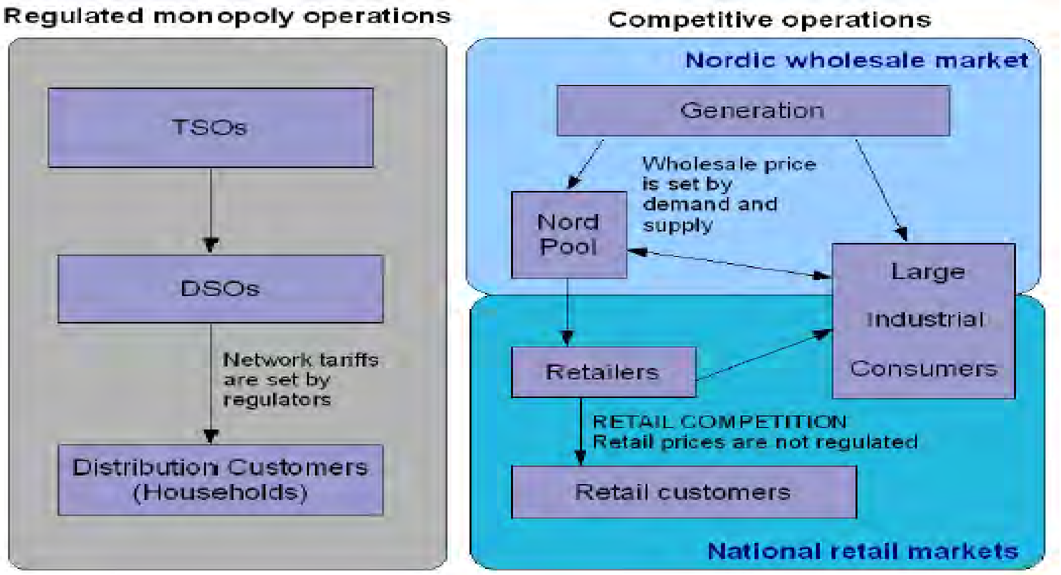


Figure 37: Nordic electricity market before and after the restructuring (Tuovinen, 2009)

In 2012, 77% of all the electricity consumed was bought on day-ahead market Elspot (Nord pool spot, 2013). Figure 38 below illustrates daily routines of Elspot trading.

In the day-ahead Elspot market takes place auction of power for delivery the following day. Prices are calculated based on supply, demand and transmission capacity (Nord pool spot, 2013).

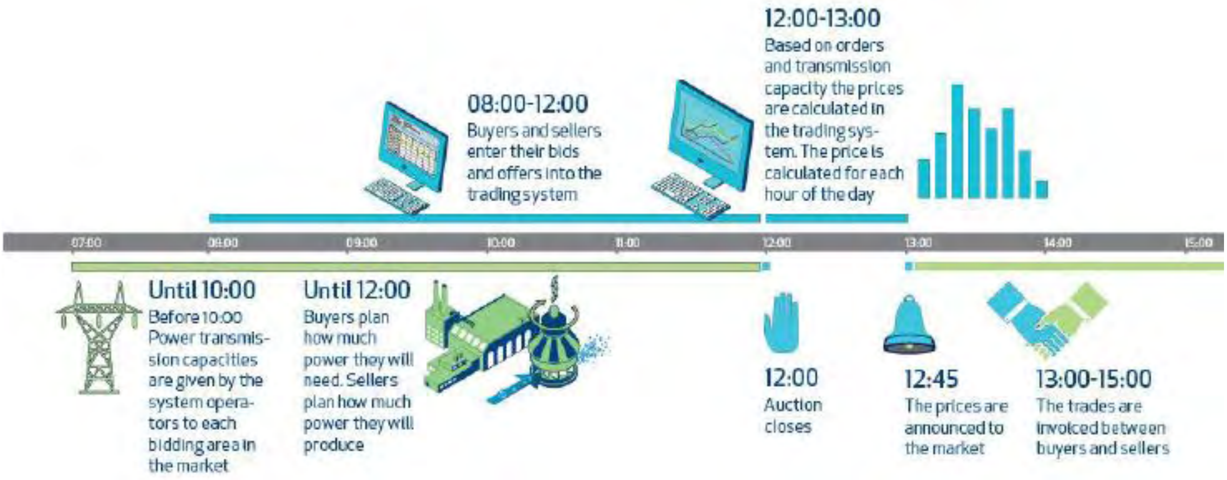


Figure 38: Elspot trading daily routines (Nord pool spot, 2013)

As for the intra-day market Elbas, it is a continuous market where power trading takes place until one hour before the power is delivered. Members can adjust their power production or consumption plans close to delivery. Every day, transmission system operators publish their power transmission capacity to Elbas. Members offer how much power they want to sell and buy and at what price. Trading is then set based on a first-come, first-served basis between a seller and a buyer. If transmission capacity is available, neighboring countries can trade on the Elbas market (Nord pool spot, 2013).

The retail market consists of retailers and retail customers. Regulators create the rules and framework for the market. Electricity retailing is primarily financial operations as the actual delivery of electricity to consumers is taken care by DSOs.

Retailers act as an intermediate between the wholesale market and end consumers. Retailers may have own production or distribution or they can be totally independent. Deregulated market has created new challenges for the retailers.

Electricity retailing has in general small margins and high risks. Retail competition can be defined as the ability of a customer to choose a preferred retail supplier. Consumers can choose from which retailer to buy their electricity according to their preferences. Most commonly the motivator to switch is the price and possible savings. Price of electricity is composed of three parts, the price of electric energy, taxes and the network tariff, from which only the price of electric energy is under competition. In addition to price competition, competition in electricity retailing is generally expected, for example, to improve customer services, create innovations, bring choice of commercial offers to customers and improve security of supply by transmitting high wholesale prices to end-users in scarcity periods (Tuovinen, 2009).

Nord pool is also a unique example of zonal deviation. Nord pool covers five areas, Norway, Sweden, Finland, East Denmark and West Denmark and potentially up to eight congestion zones since Norway may be divided into four zones as illustrated in Figure 39.

“In general, due to a weak level of interconnection between countries with respect to national grid density, the first determinants of congestion zones are national borders. Secondly within Norway different zones are defined due to internal bottlenecks” (Boisseleau, 2004).

Figure 39: Zonal approach for Nord pool (Boisseleau, 2004)

As we explained transmission congestion creates different price at each location. The use of locational prices has been described as being too complex, with the implication that an alternative approach would produce a simpler system. A common response to this assertion has been to recommend a "zonal" approach that would aggregate many locations into a smaller number of zones. The assumption has been that this would tend to reduce complexity. However, Hogan (1998) disagrees with this approach and provides a number of examples in his analysis which show that the simplest model is the nodal one, with different prices in each location.

Although the Nordic pool model is described as a zonal approach, the system operator has the possibility to change the definition of zones daily or hourly with respect to transmission constraints. This system can be better described as a nodal pricing system (Boisseleau, 2004).

Indeed, “Nord pool is continuously investigating new ways of dividing up the joint Nordic electricity market according to structural bottlenecks in the grid and independently of national borders to reflect actual physical constraints in the grid and thus provide market players with better signals as to where surplus and shortfall areas are located” (Boisseleau, 2004).

Nord pool system is generally considered to be successful. “One of the key elements of its success is the development of a common cross-border mechanism managed by a common institution formed by the system operators that directly run the power exchange” (Boisseleau, 2004).

5. Conclusions

The pool-based, short-term, competitive electricity market radically changes the traditional way markets work. Consumers play a significant role in the electricity market restructuring. Their contribution in the price determination is very important. Consumers are no more price-takers. Now they are price-makers and generators play the role of price-takers. Generators compete to each other in order to satisfy the producers' demand. The system operator takes the bids from generators and consumers and provides the equilibrium price, in order to balance supply and demand, every half hour in the spot market. In addition to that, long term market contracts provide hedging to mitigate the risks of price fluctuations and volatile congestion rentals. Finally, scheduling and balancing methods occur in order to deal with what is called day-ahead bidding. The objective of the pool-based, short-term, competitive electricity market is to optimize the benefits both for producers and consumers.

Of course, the continuous growing in demand for electricity and many other challenges of the grid, like reliability and efficiency, are significant drivers of the competitive electricity market. Supply of electricity must always equal demand, because electricity is vital in our cotemporary way of living. Also costs of blackouts and failures in the grid have really huge impacts in our societies. In the competitive electricity market higher prices produce lower demands for the consumers, in order to meet the supply in high peak demand periods.

However nothing of these would be possible without the technology development and the smart grids. Many state of the art technologies like monitoring and control, demand response systems, transmission enhancement applications, advanced metering infrastructure and of course information and communication technologies, provide the grid with all these tools needed it, in order to meet the growing challenges.

Greater interconnectedness, renewable energy and price-directed demand drive the evolution of the conventional power grids towards intelligent power networks.

Lastly, the smart grid helps us not only to reduce the costs and make a more reliably energy system, but also smart grid helps us meet the huge environmental challenges that this world face. Smart grid is a step forward to a more sustainable and "greener" planet.

6. References

ABB, (2009), Towards a smarter grid, ABB's Vision for the Power System of the Future, ABB White Paper.

Boisseleau F., (2004), The role of power exchanges for the creation of a single European electricity market: market design and market regulation.

Boyle G., (2009), Renewable Electricity and the Grid: The Challenge of Variability, Earthscan, London.

Ekanayake J., Liyanage K., Wu J., Yokoyama A. and Jenkins N., (2012), Smart Grid Technology and Applications, John Wiley & Sons.

Electric Power Research Institute (2011), Estimating the Costs and Benefits of the Smart Grid. A Preliminary Estimate of the Investment Requirements and the Resultant Benefits of a Fully Functioning Smart Grid, Palo Alto.

Eskeland G., Rive N. and Mideksa T., (2008), European Climate Goals for 2020 and the Role of the Electricity Sector, CICERO mimeo.

Faruqui A., (2010), Unlocking the €53 Billion Savings from Smart Meters in the EU: how increasing the adoption of dynamic tariffs could make or break the EU's smart grid investment, Energy Policy.

Faruqui A., 2011, Dynamic pricing the top 10 myths, UIT Interdisciplinary Energy Conference.

Gridwise Alliance (2013), Defining a Smart Grid Future
[URL]http://www.gridwise.org/smartgrid_whatis.asp

Hogan W., (1998), COMPETITIVE ELECTRICITY MARKET DESIGN: A WHOLESALE PRIMER, Center for Business and Government John F. Kennedy School of Government, Harvard University.

International Energy Agency (2010), Energy Technologies Perspectives, Scenarios and Strategies to 2050.

International Energy Agency (2011), Technology Roadmap, Smart Grids.

International Energy Agency (2013), Tracking Clean Energy Progress, IEA Input to the Clean Energy Ministerial.

Kirschen, D.S and G. Strbac., (2004), Fundamentals of Power System Economics. NJ John Wiley & Sons.

Kockar I., (2003), Combined Pool/Bilateral Operation in Electricity Markets, Department of Electrical and Computer Engineering, McGill University.

McConnell Brief (2013), [URL]http://highered.mcgraw-hill.com/sites/dl/free/0073511463/941481/mcconnell_brief2e_sample_ch03.pdf

Parker D., (2002), Research highlights from a large scale residential monitoring study in a hot climate, Florida Solar Energy Center, Florida.

Rodriguez J., (2010), Smart Grid Insights: Smart Appliances, Zpryme Research & Consulting.

Roehr A., (2010), Distributed Generation: Giving Customers a Choice in Energy Sources, Capgemini.

Schmitt L., (2009), ALSTOM Energy Management Business: EMB Strategy for Smartgrids, ALSTOM, Paris.

Stoft S., (2002), Power System Economics, Designing Markets for Electricity, IEEE Press & WILEY-INTERSCIENCE.

Tuovinen K., (2009), Retail Competition in the Nordic Electricity Markets, Department of Energy Technology, Helsinki University of Technology.

U.S. Department of Energy (2009), The Smart Grid: An Introduction.

U.S. Department of Energy (2010), Understanding the benefits of the Smart Grids, National Energy Technology Laboratory.

U.S. Department of Commerce (2010), NIST Framework and roadmap for Smart Grid Interoperability Standards, Release 1.0, National Institute of Standards and Technology.

Van Der Zanden G-J., (2011), The smart grid in Europe: The impact of consumer engagement on the value of the European Smart Grid, Lund, Sweden.

Van Der Putte J. & Short R., (2011), Battle of the Grids, Report 2011, Greenpeace.

APPENDIX

International Energy Agency - Energy Technology Perspectives 2010

The ETP BLUE Map Scenario aims to ensure that global energy-related CO2 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 temperatures of 2oC to 3oC, but only if the reduction in energy-related CO2 emissions is combined with deep cuts in other greenhouse-gas 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.

We can see more specific what these scenarios mean for the electricity supply and demand.

Electricity Demand in the Baseline and the Blue Map Scenario

Electricity demand in the Baseline scenario increases on average by 2.0% a year between 2007 and 2050, making electricity the fastest-growing component of total final demand (Figure A1). Electricity demand increases from 16 999 terawatt-hours (TWh) in 2007 to 42 655 TWh in 2050. Electricity’s share of final demand increases from 17% in 2007 to 23% in 2050. These trends are driven by rapid growth in population and incomes in developing countries, by the continuing increase in the number of electricity-consuming devices used in homes and commercial buildings, and by the growth in electrically driven industrial processes (IEA, 2010).

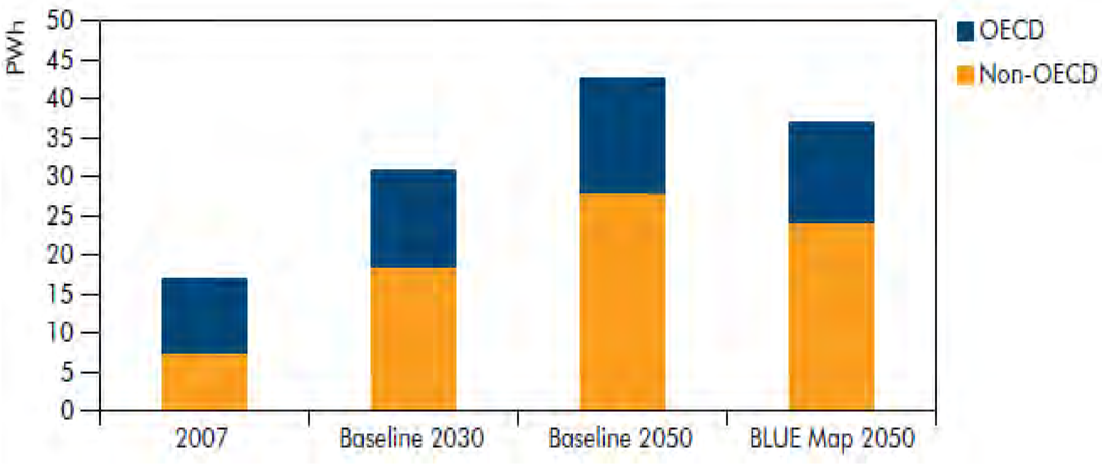


Figure A1: World electricity demand by scenario (IEA, 2010)

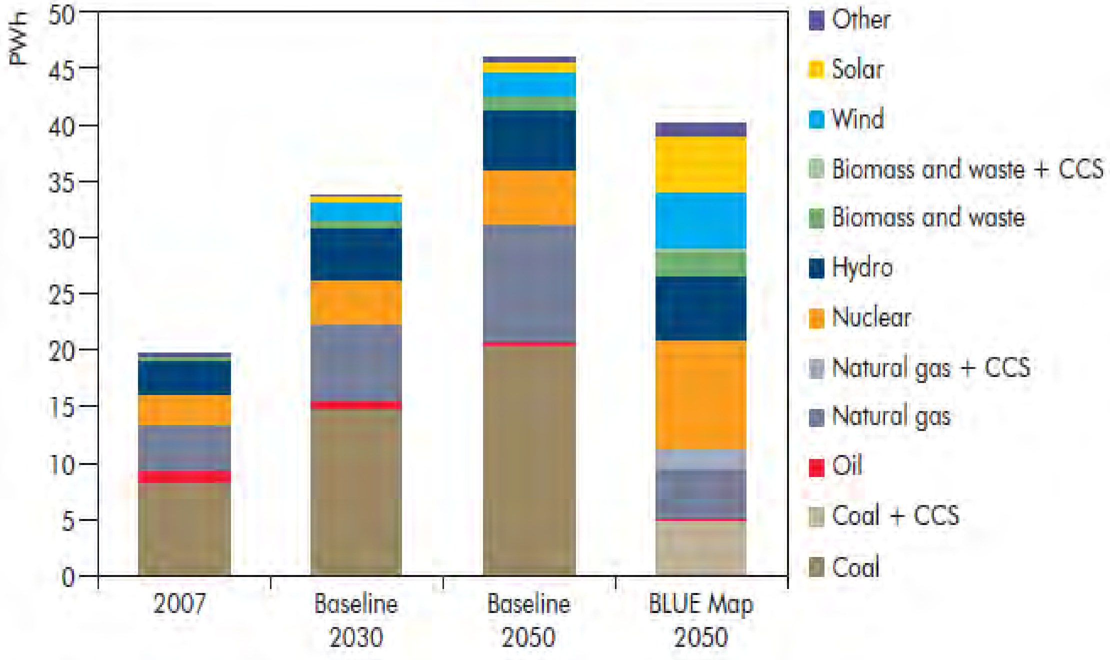
Significant efficiency improvements reduce electricity demand in the BLUE Map scenario as compared with the Baseline scenario.

Baseline electricity demand in non-OECD countries grows on average by 3.1% a year, almost three times as fast as in OECD countries. This is primarily due to higher population growth and rapid increases in GDP and per-capita incomes in developing countries. Between now and 2050, tens of millions of people in developing countries will gain access to electricity.

In the BLUE Map scenario, global electricity demand growth is reduced to an average of 1.8% a year, with demand reaching 36 948 TWh in 2050. Electricity demand in 2050 is 13% below the Baseline scenario level. Electricity savings occur mostly in the buildings sector and in industry in the BLUE Map scenario, but these are partially offset by increased electricity demand in the transport sector as a result of the uptake of PHEVs (plug-in hybrid electric vehicles) and EVs (electric vehicles) (IEA, 2010).

Electricity Production in the Baseline and the Blue Map Scenario

In the Baseline scenario, global electricity production increases by 134% between 2007 and 2050 (Figure A2). Fossil fuels maintain their high share in the electricity generation mix, accounting for two-thirds of the total. In 2050, coal-based generation is 149% higher than in 2007, accounting for 44% of all power generation. The share of gas-fired power generation increases slightly to 23%, while oil is almost completely phased out. Nuclear decreases to 10%, hydro decreases to 12%, and wind increases to account for 5% of all power generation. As a result of the continued dependence on fossil fuels, CO2 emissions from electricity generation will almost double between 2007 and 2050 (IEA, 2010).



Note: Other includes electricity generation from geothermal and ocean technologies.

Figure A2: Global electricity production by energy source and by scenario (IEA, 2010)

There is a major shift from fossil fuels to low-carbon alternatives in the BLUE Map scenario.

As we said earlier, electricity demand in 2050 in the BLUE Map scenario is 13% lower than in the Baseline scenario owing to increased energy efficiency in the end-use sectors. This is despite the fact that some of the increased efficiency in industry and buildings is offset by higher demand for electricity for additional uses, such as heat pumps and plug-in hybrid vehicles (PHEVs) and electric vehicles (EVs).

As well as reducing electricity demand, the CO2 emissions reduction incentives and other measures introduced in the BLUE Map scenario radically change the electricity generation mix relative to the Baseline scenario. Low-carbon energy sources, such as nuclear and renewables, become more attractive compared to fossil-fuelled power. By 2050, a variety of renewables generate almost half the electricity in the BLUE Map scenario and nuclear increases its share to 24%. Coal-fired generation reduces to 12% by 2050, more than 90% of which is combined with CCS. Gas-fired generation is also much lower than in the Baseline scenario with a 15% share, of which almost one-third is fitted with CCS (IEA, 2010).