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Μεταπτυχιακή Διπλωματική Εργασία

Λάμπρος Σαμαράς

Επιβλέπων: Δημήτριος Μπαργιώτας

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UNIVERSITY OF THESSALY

SCHOOL OF ENGINEERING

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

Renewable Energy Integration into Smart Grid Energy Systems

Problems and Solutions

MSc Thesis

Lampros Samaras

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Ευχαριστίες

Πρώτα και κύρια, θα ήθελα να ευχαριστήσω των επιβλέποντα καθηγητή μου κ. Μπαργιώτα Δημήτριο για τη συμπαράσταση και βοήθειά του κατά την εκπόνηση της παρούσας εργασίας. Επίσης, ευχαριστώ τα μέλη της οικογένειάς μου για τη βοήθειά τους με τον δικό τους έμμεσο τρόπο κατά τη διάρκεια της δουλειάς μου για την ολοκλήρωσή της εργασίας.

Μεταπτυχιακή Διπλωματική Εργασία

Ενσωμάτωση Ανανεώσιμων Πηγών Ενέργειας

στο Έξυπνο Δίκτυο Ηλεκτρικής Ενέργειας

Λάμπρος Σαμαράς

Περίληψη

Η απεξάρτηση της οικονομίας από τη χρήση ρυπογόνων καυσίμων με τη συνεπακόλουθή μείωση των εκπομπών αερίων του θερμοκηπίου στην ατμόσφαιρα, αποτελεί βασική προτεραιότητα πολλών κρατών διεθνώς – συμπεριλαμβανομένων της Ελλάδας και της ΕΕ – με σκοπό την άμβλυνση των επιπτώσεων της κλιματικής αλλαγής. Στην επίτευξη αυτού του στόχου, κομβικό ρόλο θα διαδραματίσουν οι Ανανεώσιμες Πηγές Ενέργειας, αφού είναι αναγκαίες για την αντικατάσταση των υπαρχόντων ρυπογόνων μονάδων παραγωγής.

Η ενσωμάτωση των ΑΠΕ στο δίκτυο είναι επιβεβλημένη μέσω της συνεχής αύξησης της Διεσπαρμένης Παραγωγής τόσο στο Δίκτυο Μεταφοράς όσο και στο Δίκτυο Διανομής. Όμως η υψηλή διείσδυση των ΑΠΕ φέρνει στο προσκήνιο την αβεβαιότητα και τη μεταβλητότητα που τις χαρακτηρίζουν· δημιουργώντας έτσι νέες προκλήσεις και προβλήματα για τα Δίκτυα Ηλεκτρικής Ενέργειας που δεν υπήρχαν στο παρελθόν.

Οι προκλήσεις αφορούν κατά κύριο λόγο την ελαστικότητα του δικτύου και απαιτούν καινοτόμες λύσεις που στοχεύουν στην εισαγωγή «ευφυΐας» στο Δίκτυο ΗΕ και συγκεκριμένων μεθόδων – κανονισμών ώστε να αντιμετωπιστούν αποτελεσματικά οι δυσμενείς επιπτώσεις. Σκοπός της παρούσας διπλωματικής εργασίας είναι η ολοκληρωμένη ανασκόπηση του θέματος και η εμβάθυνση των προτεινόμενων λύσεων.

Λέξεις-κλειδιά:

Ανανεώσιμες Πηγές Ενέργειας (ΑΠΕ), Μείωση Εκπομπών Αερίων Ρύπων, Δίκτυο Ηλεκτρικής Ενέργειας, Υψηλή Διείσδυση των ΑΠΕ, Ηλιακή Ενέργεια, Αιολική Ενέργεια, Φωτοβολταϊκά πάρκα, Αιολικά πάρκα, Ευφυή / Έξυπνα Δίκτυα Ηλεκτρική Ενέργειας (ΗΕ), Διεσπαρμένη Παραγωγή, Βοηθητικές Υπηρεσίες, Κώδικας Δικτύου, Αποθήκευση ΗΕ, Μπαταρίες, Υδραντλίες αποθήκευσης.

MSc Thesis

Renewable Energy Integration into Smart Grid Energy Systems

Lampros Samaras

Abstract

The decarbonization of the world economy and the subsequent reduction of the greenhouse gases emissions into the atmosphere, is the main priority of many countries – including Greece and the EU – and international organizations such as the United Nations, in order to mitigate the negative consequences of the climate change. To this end, the Renewable Energy Resources (RES) are expected to play the central role in replacing the fossil fuel power plants that cause most of current pollution worldwide.

The integration of RES into the electric grid is indispensable to achieving net zero emissions and the best way to implement that is via decentralized / distributed generation. However, the high penetration of RES in the electric grid brings forth the intermittent and variable nature of these sources, especially wind and solar power. This situation creates problems and new challenges for transmission and distribution grids that never existed before.

These challenges involve mainly the flexibility of the grid and require innovative solutions that aim to add intelligence into the existing electrical grid and to apply specific methods and regulations so as to address effectively all the adverse impacts.

The purpose of this MSc thesis is to present a comprehensive overview of the subject of Renewable Energy Integration into Smart Grid Energy Systems with an emphasis on the arising problems/challenges as well as on the proposed solutions.

Key words:

Renewable Energy Sources (RES), Gas Emissions Reduction, Electrical Grid, high penetration of RES, Solar Energy, Wind Energy, solar PV parks, Wind farms, Smart Grid, Distributed / Decentralized Generation, Ancillary Services, Grid Code, Energy Storage, Batteries, Pumped Hydro Storage.

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Abbreviations

aka	also known as
CCS	Carbon Capture and Storage
CSP	Concentrating Solar Power
DER	Distributed Energy Resources
DG	Distributed / Decentralized Generation
DSR	Demand Side Response
EU	European Union
ESS	Energy Storage Systems
EST	Energy Storage Technologies
GHG	Greenhouse Gases
IBR	Inverter-based Resources
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
NREL	National Renewable Energy Laboratory (USA)
PHES	Pumped Hydropower Energy Storage
PSH	Pumped Storage Hydropower
PST	Power System Transformation
PV	Photovoltaic
RES	Renewable Energy Sources
SCADA	Supervisory Control And Data Acquisition
SG	Smart Grid
VG	Variable Generation
VRE	Variable Renewable Energy
VRES	Variable Renewable Energy Sources

Chapter 1 Introduction

The decarbonization of the economy and the subsequent decrease of greenhouse gases in the atmosphere, is a key priority for many countries around the world, including Greece and other EU member states. The main target is the mitigation of the negative consequences to the climate change.

The greenhouse gas emissions of traditional electricity generation plants contribute to the increase of the average global temperature in the next decades. Climate change and climate crisis phenomena such as raised sea levels, extreme weather conditions, such as severe droughts, are expected to become more frequent and persistent with detrimental repercussions on human societies and the environment.

To tackle such global climate changes, it is urgently needed an energy transition that assures a cleaner and more sustainable energy supply. The 2015 Paris Agreement was a landmark in the international climate change affairs because it was the first time that 195 countries committed into a common cause and signed a legally binding agreement to undertake ambitious efforts to combat climate change. Its goal is, among others, to limit the global warming effect to well below 2°C compared to pre-industrial levels [1].

To achieve such an ambitious goal, it’s imperative to integrate high shares of Renewable Energy Sources (RES) into the electrical grid. In other words, high penetration of RES (i.e. greater than 30% and up to 80%) is absolutely necessary to effectively cope with the problem. There are even references to 100% shares, that is, a total dependance on renewables (wind, solar) and distributed energy sources (storage sources, EVs etc.) [2].

The resulting challenge is to maintain the grid resilience and reliability under the new conditions imposed by the high RES penetration without compromising the quality of the electricity services to the consumers.

During the last decade, significant amounts of Renewable Energy Sources (RES) have been installed and integrated into the electrical grid worldwide, while attempting to secure the supply and the reliance of the system.

As far as Greece is concerned, a key objective (along with the corresponding increase of RES share) is the highly ambitious reduction of the lignite portion in the power generation mix. The so-called "lignite phase-out" will put a complete end to the use of lignite by 2028 [3].

1.1 Subject of the MSc Thesis

The subject matter of this MSc Thesis is the successful integration of high shares of Renewable Energy Sources (RESs) into the Smart Grid Energy Systems in terms of the electricity production energy mix. A special emphasis is given to the arising problems and challenges of the high penetration of RESs into the Smart Grid, as well as the proposed solutions to successfully address these challenges.

For introductory and clarification purposes, the prerequisite groundwork is laid out of all the relevant basic terms and subjects. Thus, before delving into the challenges and solutions concerning the high level of RESs penetration, there are chapters referring to the Renewable Energy Sources (along with their beneficial contribution to climate change), and also to the Transmission and Distribution energy systems (traditional and smart grids). In particular, the RESs are considered as an indispensable part to the transition of the traditional energy system to the modern-day Smart Grid.

1.1.1 Contribution

The contribution of the MSc Thesis comprises a comprehensive presentation of the electrical power system challenges due to the integration of high shares of RES (as opposed to traditional energy sources), and the array of solutions that are proposed to solve the subsequent problems while ensuring the quality and supply of electricity to grid users (consumers and producers alike).

The proposed solutions are based on cutting edge technologies which are the center of today's scientific and research interest. Certain aspects regarding the efficacy and the economic viability of these solutions are still open problems.

The reader of this thesis will acquire an overview of all the aspects of the subject matter.

1.2 Structure of MSc thesis

The structure of the MSc thesis by chapter is as follows:

In Chapter 2, there is an introduction of the basics of Greenhouse Gases and anthropogenic emissions. The climate change issues they entail and the depletion of fossil fuel reserves in the foreseeable future, lead to the use of Renewable Energy Sources (RESs) as an unavoidable solution. The major types of RESs are also presented.

In Chapter 3, the elementary notions of the conventional electric power systems are presented; that is, the power generation, the transmission system and the distribution grid. Additionally, we present the new concepts and technologies the Smart Grid comprises which is the modern technological evolution of the traditional transmission system and distribution grid. The integration of RESs and DERs, as well as the control and communication infrastructures, are indispensable to the Smart Grid concept.

In chapter 4, we discuss the issues of RESs penetration to the grid. The chapter is divided in two sections. The first section refers to the problems and challenges of the high RES penetration, whereas the second section gives particular emphasis to the solutions. Although the challenges are mostly known, the proposed state-of-the-art technologies, their exact deployment, efficacy, and viability with respect to the peculiarities of grid-specific cases are still the center of today's research interest. However a lot of progress has been achieved already and the path towards 100% RES penetration seems more feasible than ever before.

Finally, in chapter 5 we draw conclusions based on the subject matters discussed in previous chapters and we present the future perspectives and the open research areas.

Chapter 2 Renewable Energy Sources

2.1 Introduction

A consistent increase in global energy consumption is observed in the last decades, giving rise to environmental concerns since more than half of the electricity generated (63.1% in 2019) comes from fossil fuel sources (i.e. coal, natural gas, and crude oil), as illustrated in Figure 2.1 below.

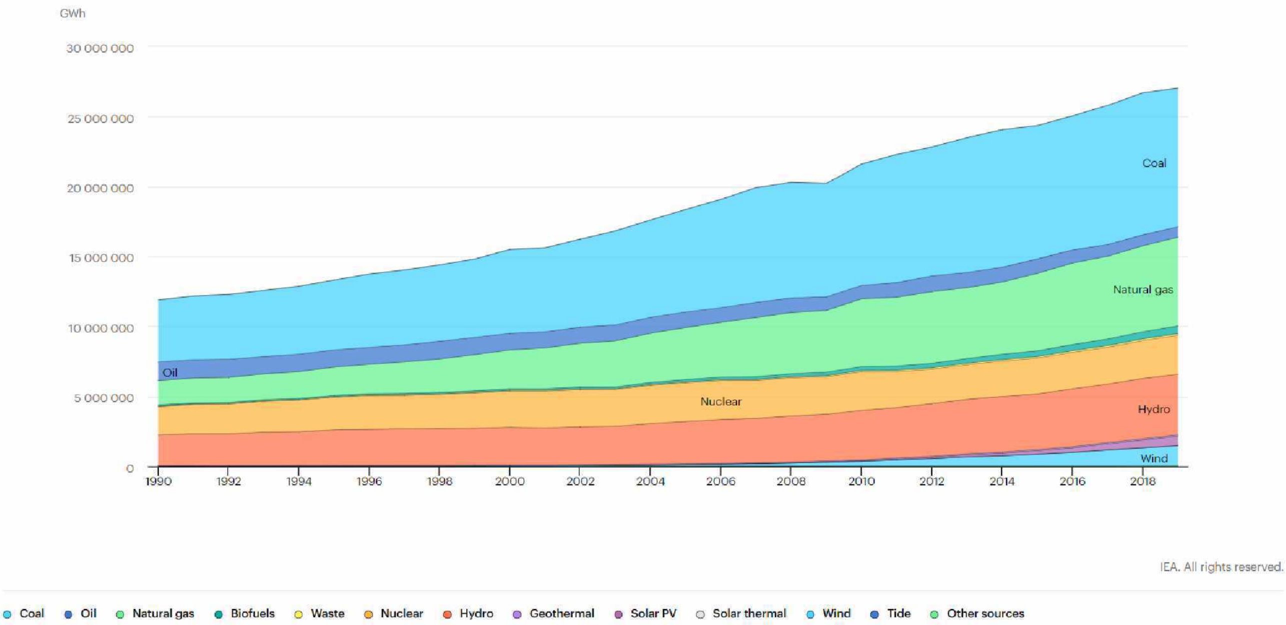


Figure 2.1 Electricity Generation by source from 1990 to 2019 (source: IEA [4])

Due to this increasing consumption trend and the widespread use of coal, natural gas and crude oil (aka petroleum), the greenhouse gases (GHG) in general and CO_2 emissions in particular keep rising (Figure 2.1) thus contributing to climate change with damaging impacts on ecosystems and human societies. By reducing air pollution, we can effectively protect the climate [5]. International organizations and many national governments have set net-zero (aka carbon neutrality) targets to be met by 2050.

Most natural resources are gradually diminishing and their depletion poses a serious problem for the world energy needs in the coming decades [6, 7]. As an alternative, Renewable Energy Sources can be used in order to minimize the global dependency on fossil fuels. This energy mix transition could drastically reduce GHG emissions and thus restrict or even revert the climate change consequences.

2.1.1 Fossil Fuels

Many countries around the world are currently implementing ambitious plans to limit their dependence on fossil fuels; however, the global energy demand is still rising. The "Global Energy and CO_2 Status Report 2018" of the International Energy Agency (IEA) shows that the energy demand increased by 2.3%; the highest in a decade [8].

At least 70% of the 2018 energy demand was met with fossil fuels (coal, crude oil and, natural gas). As a result, the energy related carbon emissions increased by 1.7%. Coal-related power generation continues to be the single largest emitter, accounting for 30% of all carbon dioxide emissions related to energy generation [8]. Nevertheless, fossil fuel reserves are diminishing and the economy cannot rely on them for long in the future.

Fossil fuels were formed in former geological periods, millions of years ago. They were created from the remnants of dead plants, animals, organisms which were compressed and heated, finally being fossilized under soil deposits. Over millions of years, these fossilized deposits created carbon-rich fuel resources such as petroleum, natural gas and coal.

Even now, fossil fuels are still formed by natural processes in the earth's crust, but they are considered as non-renewable sources because it takes millions of years to develop and the use of known reserves is at such rate that their depletion is much faster than their generation.

It's worth noting that the impending depletion of fossil fuel reserves is not the main reason that makes them an inappropriate energy resource, but rather the argument that the 2 degree upper limit of the Intergovernmental Panel on Climate Change (IPCC), may be reached well before the world reserves are run out [9]. The Intergovernmental Panel on Climate Change (IPCC) was founded in 1988. Its main goal was to assess the climate change effects on behalf of the United Nations.

At the current rate of fossil fuel consumption, the reserves are expected to be depleted within the 21st century [6], but most importantly if we are to achieve the desirable goal of not exceeding the 1.5°C of average global warming limit by 2050, most of the fossil fuel reserves (58% of petroleum, 59% of natural gas and 89% of coal) must remain unused [10].

Renewable Energy Sources (i.e. wind and solar) appear to be the only viable alternative. These resources are renewable in the sense that they will not ever run out. Furthermore, they are environmentally friendly because they produce minimal or no GHG emissions when used for electricity generation [11].

2.1.2 Greenhouse Gases and anthropogenic emissions

The primary greenhouse gases (GHGs) in the atmosphere are: H_2O (water vapor), CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide) and O_3 (ozone). In the absence of greenhouse gases, the average temperature of the surface of the Earth would be approximately −18°C, rather than 15°C which is the Earth's present average temperature [12].

The Earth's greenhouse effect is determined by the concentration of a few GHGs in the atmosphere. Water vapor is the one that causes the most of overall warming.

However, due to human activities, large quantities of anthropogenic GHGs are directly emitted into the atmosphere that change the natural concentration mix in such a significant way that the greenhouse effect is getting stronger causing temperature, sea level and climate changes that consequently have negative impacts on the environment and life (flora and fauna). Human activity affects indirectly the water vapor level in the atmosphere.

The greenhouse gases, that the human activities are responsible for their increased atmospheric concentrations, are (in decreasing order of average global concentration and warming impact):

- Carbon dioxide (CO_2). It's responsible for the three quarters of the warming effect of anthropogenic emissions. The main sources of CO_2 emissions are i) the fossil fuels burning (i.e. coal, crude oil, and gas) and ii) the deforestation.
- Methane (CH_4). Accounts for about 14% of the impact of the present anthropogenic GHG emissions. The key methane sources are i) agriculture (e.g. rice fields and livestock), ii) fossil fuel extraction and iii) the organic waste decay in landfills.
- Nitrous oxide (N_2O). Responsible for nearly 8% of the warming effect of anthropogenic GHG emissions. Human activities such as agriculture (e.g. livestock waste, nitrogen-fertilized soils etc.) and industrial processes are increasingly contributing to large shares of nitrous oxide in the atmosphere.

- Fluorinated gases (aka "F gases"). Account for around 1% of the warming effect of anthropogenic GHG emissions. The F-gases emissions are due to industrial processes.

It's worth noting that whereas the above order is in decreasing warming impact, the warming (heat-trapping) effect per gram of gas is in increasing order for the above mentioned GHGs.

Moreover, the gradual depletion of the natural fossil fuel reserves creates an urgent situation regarding the availability of energy in the future. It is not possible to satisfy our increased energy needs sustainably by exploiting energy sources that are not renewable. Hence, it is imperative for the global economy to turn to renewable energy alternatives.

The technological development of Renewable Energy Sources (RESs) provides with solutions to the aforementioned problems, so that a successful replacement of conventional resources with renewables can gradually take place. In this way, the climate change negative effects will be mitigated and sustainability will be achieved.

Nearly 40% of global CO_2 emissions are due to electricity generation via fossil fuels combustion in order to generate the heat needed to power steam turbines. The fossil fuels burning results in the production of large quantities of carbon dioxide (CO_2). Carbon dioxide is considered the primary greenhouse gas for global warming. The application of smart grid technologies can be conducive to the reduction of CO_2 emissions.

Electricity systems comprise three major sectors: generation, transmission and distribution grid, and consumption. Smart generation comprises various types of renewable energy sources such as wind, solar and hydropower [13].

An important parameter of energy technologies is the so-called CO_2 footprint, since CO_2 is the most important greenhouse gas (GHG) in terms of environmental impact. Its contribution to the anthropogenic GHG emissions exhibits an increase from 72% in 1970 to 76% in 2010 [14, 15]. The long term predictions show that the content of CO_2 will reach 600 ppm by 2100 [16] thus exacerbating the climate change effects [17]. The CO_2 footprint of all energy technologies need to be thoroughly investigated if we aim to successfully mitigate the imminent perils of climate change.

2.1.3 What is Renewable Energy?

Renewable Energy is a term used to refer to several types of energy sources which are derived from earth's natural resources that are neither finite nor exhaustible. Renewable energy can be deemed as an alternative to the conventional energy which mostly depends on fossil fuels. Although conventional energy is harmful for the environment, in contrast, renewable energy is considered to be environmentally friendly.

Non-renewable energy sources include petroleum, natural gas and coal. Once these sources are totally used up, they cannot be replenished. Oil and natural gas production is expected to peak soon when the "Hubbert peak model" is applied [18]. According to certain studies, their gradual depletion is expected before the end of the century and even as close as some time about 2070 [19].

Nuclear energy is often considered as non-renewable although there are some details and specificalities that make it a special case. Therefore, it is as discussed separately in §2.3.7.

2.2 Renewable Energy and Greenhouse Gas emissions

Apart from being inexhaustible, another important aspect of the Renewable Energy Sources (RES) is the absence of GHG emissions.

Although the combustion of coal, natural gas and distillate fuel (i.e. products of crude oil such as diesel, petrol, kerosine etc) produce carbon dioxide, the renewable energy power systems do not emit GHG, i.e. their energy source is carbon free. If fossil fuel generation is replaced by renewable energy electricity systems, the amount of anthropogenic GHG emissions into the atmosphere, can substantially be decreased.

The case of Biomass energy systems deserves a special explanation. Although Biomass systems utilize combustion and emit carbon dioxide, these emissions are essentially carbon dioxide neutral. The carbon dioxide produced by combustion, is not considered to increase the amount of GHGs in the atmosphere because that very amount of carbon dioxide was removed from the atmosphere by plants in the first place. That is, the carbon dioxide was removed in the recent past as part of the natural global carbon cycle. Even if no electricity was generated, the decay of biomass would have produced the same amount of carbon dioxide anyway. However, fossil fuels are different, since their carbon content was captured millions of years ago. Therefore, when fossil fuels are used to generate electric power, carbon dioxide that was captured and otherwise would not have been emitted, is now accumulated to the atmosphere [20].

2.3 Types of Renewable Energy Sources

The main types of renewable energy sources (RES) are the following:

- Wind
- Solar
- Hydroelectric
- Biomass and Biogas
- Geothermal
- Ocean / Tidal
- Hydrogen

These forms of RESs refer to technologies that exploit various natural energy resources (e.g. sunlight, wind, tidal waves etc) in order to convert it to electricity which then will be injected into the electrical grid; either directly to the transmission or the distribution grid. As an intermediary phase, the renewable energy may be converted to another form of energy (e.g. kinetic energy) before it is finally transformed into electricity. For example, the wind energy is firstly converted into kinetic energy through the blades and the rotor, and then a generator converts the kinetic energy of the rotor into electricity.

In Greece, the hydropower share of the total power generation is around 10%, although the rest of the renewables contribute more than 21% as of 2018 [21].

In the following paragraphs, we discuss briefly the main types of RESs.

2.3.1 Wind

Wind is a terrestrial meteorological phenomenon. Its primary cause is the solar energy which gives rise to temperature differences in different places. The uneven heating of the earth causes differences in the atmospheric pressure which in turn results in air movement i.e. wind.

Wind Energy derives from the winds in the Earth's atmosphere which is a natural and infinite source. Wind power is the power derived by harnessing the directional movement of air (wind) and its conversion to useful forms of mechanical power and electricity. By means of wind energy conversion systems (e.g. wind turbines), the kinetic energy of the wind can be transformed into electricity. It is also clean since no harmful gases are produced during the electricity generation.

According to an estimate by the World Energy Council [WEC 2013], even if only 1% of the planet's surface was used for wind energy generation, that would be sufficient to cover the total worldwide electricity needs [22, 23].

Wind energy growth

Wind energy has been a fast-growing RES since the beginning of the century, as shown in Figure 2.2, with global capacity that consistently exceeds solar capacity and is second only to hydroelectric power (aka hydropower or hydro). In 2020, the wind capacity growth almost doubled as compared with 2019; that is, 111GW of added capacity compared to 58GW the previous year [25].

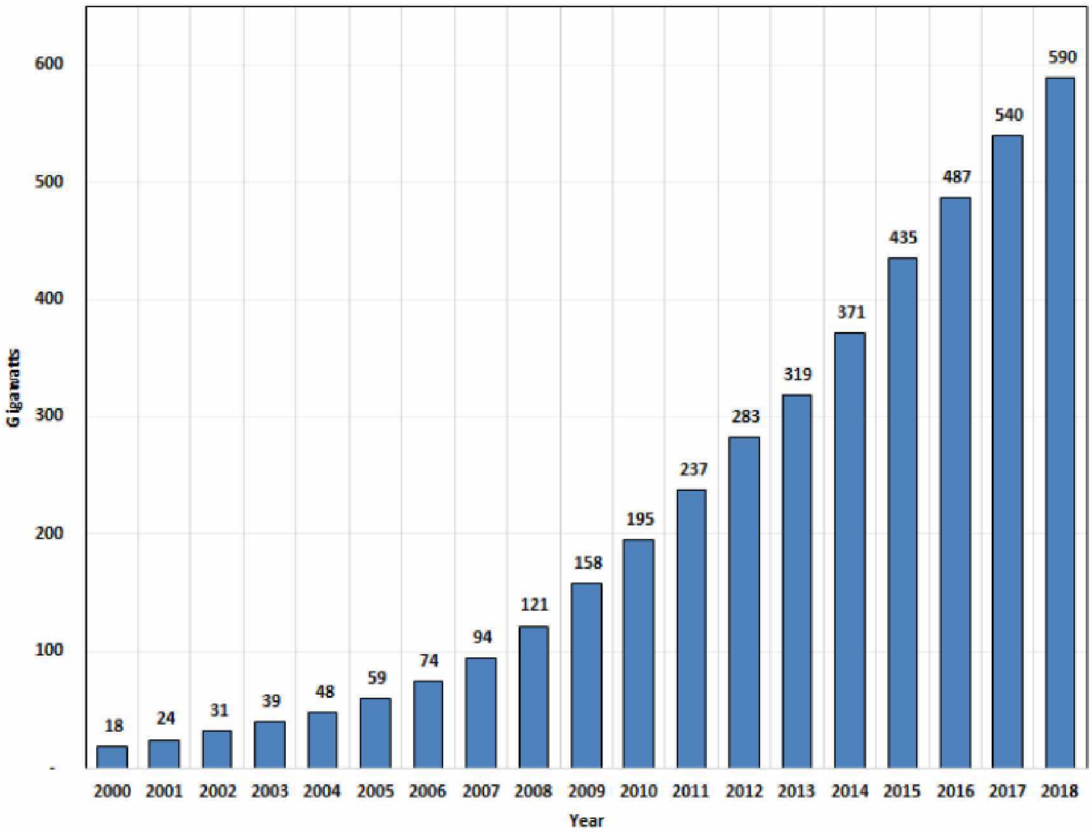


Figure 2.2 Global wind energy capacity growth since 2000 [24]

Wind energy is emerging as a very significant power resource together with renewables as well as conventional energy resources. European countries are the leaders in this trend. The wind market is also growing fast in the United States because of policy support. Recently, China and India have entered the wind market in a very dynamic way. Many other countries are introducing policies and regulations friendly to wind generation as well.

As of 2021, the 6 countries with the highest wind capacity in decreasing order are China (329TW), the USA (133TW), Germany (64TW), India (40TW), Spain (27.5TW) and the UK (27TW).

In Greece, the wind contribution to the total power generation exceeded 13% in 2018 [21]. There is a lot of interest in wind energy due to the high aeolic (wind) potential in many parts of the country and especially on islands. The wind power capacity was 4,457 MW in 2021 [26].

Benefits of Wind Power

The following benefits of wind power explain the fact that it is one of the fastest growing renewable energy resources.

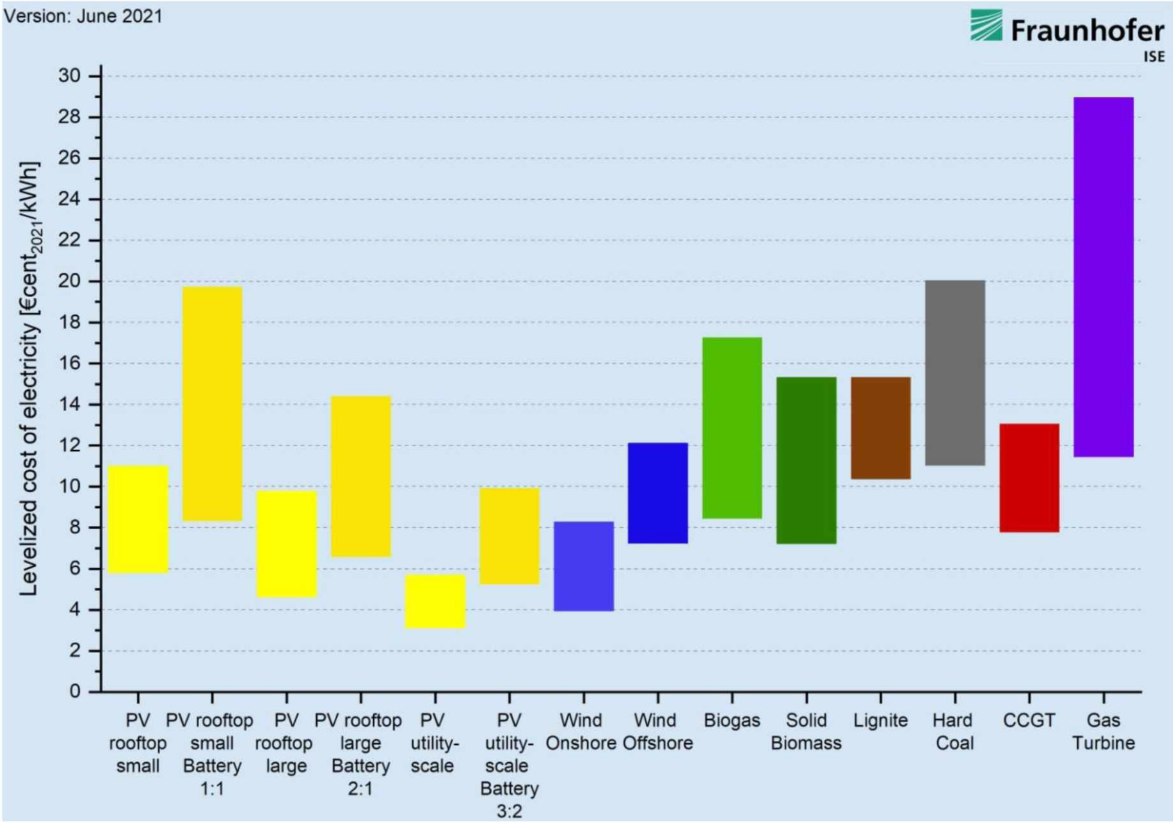
- Cost-effective. On-shore wind farms energy production is one of the lowest priced sources because operational cost is low since its "fuel" (i.e. wind) is at no cost. It's second only to solar PV due to the initial high capital costs.
- Economy. It is good for the economy in general because it creates new jobs and contributes to the wind industry growth.
- Sustainable and clean source. The sun shines and thus it is triggering the wind to blow, therefore the wind energy can be harnessed practically ad infinitum; hence sustainable. Wind power generation does not pollute the environment with GHGs like the conventional thermal power plants do [27, 28, 29].

Disadvantages of Wind Power

Further research aims at addressing the challenges of wind technology, cost and integration.

- Capital Cost. Primarily the initial capital cost that includes construction and implementation phases, and secondarily the maintenance cost can be quite significant especially in the case of off-shore systems, and even more so if storage is involved [27]. However, these costs are constantly declining to the point that in recent years they are very competitive comparing to other renewable energy (RE) technologies and traditional power plants as a new study in Germany suggests [30]. The LCOE (levelized cost of electricity) of various energy sources is illustrated in Figure 2.3 for comparison.

- Inappropriate locations. Many sites with considerable wind potential have already been exploited. Of those remaining, some cannot be exploited for environmental reasons while others may not be as windy enough. Lastly, there are locations of rich resource potential but are located very far from residential areas with no grid infrastructure and therefore are not economically viable. New transmission lines may be needed which add to the capital cost of the project [28].
- Noise, aesthetic pollution and wildlife impacts. There are concerns about the noise produced by the blades, but the wind turbines are usually installed far from residential areas and so in most cases it's not much of a problem. Also, some consider the wind farms as an eyesore although others do not share this view. Finally, it is true that spinning blades can be lethal for birds and bats. The presence of wind farms may alter the habitat of some animals and even make it unsuitable. Ongoing research aims to mitigate these issues [29].



- Figure 2.3 LCOE of RE technologies & conventional power plants in Germany in 2021 [30]

Capacity Factor and Power Curve

The Capacity Factor (CF) is as the ratio of the electrical energy of a generating unit for a certain period of time, to the peak electrical energy, that is, the energy produced when the generating unit is operating at full power for the same time period [IEA]. In simple terms, it's the fraction of the year that the turbine generator operates at peak power (rated power). The formula is as follows:

$$CF = \frac{Average\ Output}{Peak\ Output}$$

Generally, the CF is influenced both by the wind turbine and the site characteristics. It is typical for a good site that CF is equal or greater than 0.3 (30%) for modern-day wind turbines.

Betz Law

The Betz law postulates an upper limit to the maximum efficiency of any wind energy system, that is, the maximum power that can by captured from the wind. Specifically, according to the Betz limit, it is possible to convert no more than 59.3% of the wind kinetic energy into mechanical energy using a wind turbine.

The factor 59.3% or 16/27 is also known as Betz coefficient and is the maximum efficiency for any wind turbine. Good turbines have a coefficient in the range of 35 to 45%.

Wind Turbines

The exploitation of the wind potential is done via the wind turbines. The wind turbines are machines that transform the wind energy into rotational kinetic energy and then through generators into electricity. There are various types of turbines but the most widespread are the horizontal axis ones. The wind speed that can be harnessed by the turbines is usually from 4m/s (cut-in speed) to 25m/s (cut-out speed). The wind turbines generally appear in arrays of many turbines installed in the same area that are called "wind farms". The siting (i.e. location of installation) includes ridges, plains or off-shore locations. Due to their large capacity they are generally connected to the HV power transmission system through step-up transformers. The size of a wind turbine blade is between 50m and 125m whereas the power capacity ranges from 750kW to 5MW. Turbines of 15MW and 20MW are planned to be manufactured in the future [31].

A typical power curve of a wind turbine of 2MW peak power is shown in the following Figure 2.4. The cut-in wind speed is 4.5m/s under which there is no power generated and the rotor stops rotating. Whereas the cut-out speed (or storm protection shut-down) is 26m/s above which the rotor stops spinning (brake control is applied) to protect from damage. Within a certain range of speeds, in this case from 15 to 25 m/s, the peak power and efficiency of the wind turbine is achieved. Usually, the average wind speed at the site is between the cut-in and the rated wind speed.

The aerodynamic loss of energy is approximately 50% to 60% at the rotor. The mechanical loss is about 4% at the gear. Finally, the electromechanical loss is almost 6% at the generator. The overall efficiency is between 30% and 40% [23, NEDO 2013].

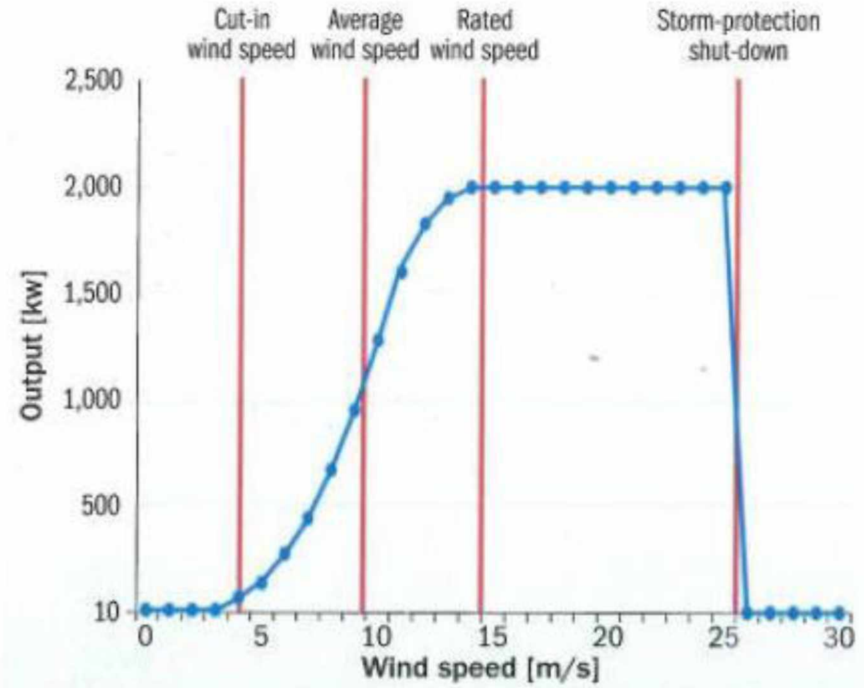


Figure 2.4 Power Curve of a typical wind turbine (source: www.windfarmbop.com)

Depending on the characteristic specified, wind power systems are primarily categorized as follows:

- Grid connectivity: connected, stand-alone
- Installation characteristic: on-shore, off-shore
- Wind turbine type: vertical axis, horizontal axis

Off-shore wind generation presents a better resource potential and lower environmental consequences than the on-shore wind generation.

The horizontal axis wind turbine systems are commonly used all over the world, on-shore and off-shore, and usually are connected to the transmission system (high voltage grid).

The power that is generated by wind turbines, is directly proportional to the length of the blades (the swept area) and proportional to the cube of the wind speed.

The wind technology is considered to be mature and no significant technical restrictions exist in the generating system that could limit its expansion. The wind generation costs are low as compared to other renewables.

The basic elements of wind turbines

The main elements of a wind turbine are: the rotor blade, the hub, the shaft, the nacelle, the brake, the gearbox, the generator. Also, the controller, the tower and the transformer. Figures 2.5 and 2.6 present diagrammatically the wind turbine components.

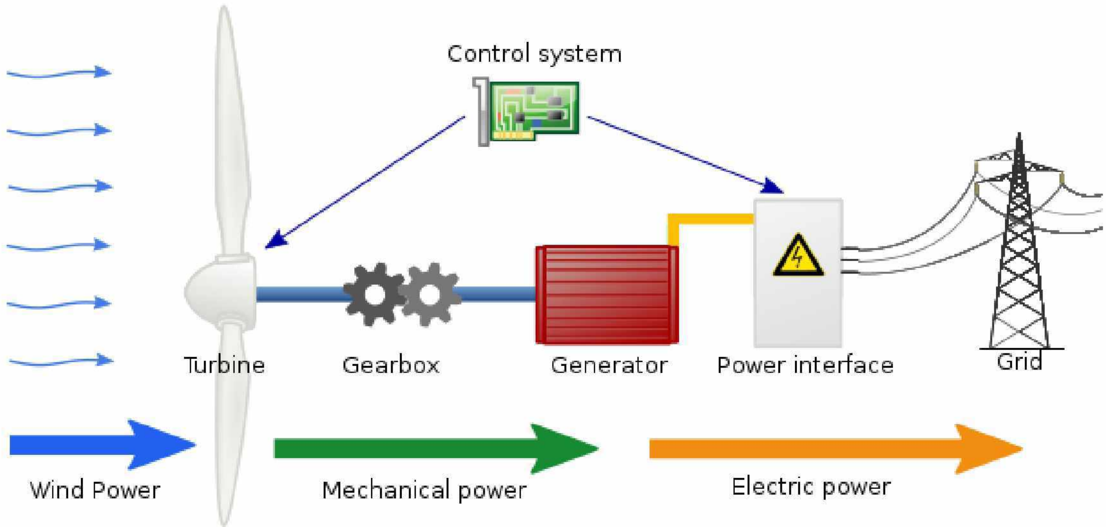


Figure 2.5 Conceptual diagram of a wind turbine (source: Wikipedia)

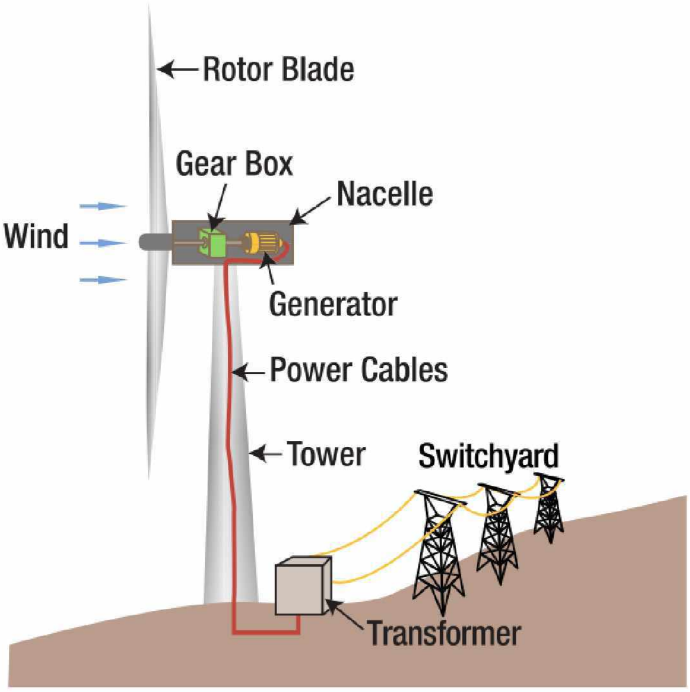


Figure 2.6 Diagram of the basic elements of a horizontal-axis wind turbine (source: Wikipedia)

The **rotor blades** receive the wind energy. In turn, they convert the wind energy into rotational energy. The number of blades is a factor that influences the efficiency and structure of the system. Usually, the horizontal-axis turbines are equipped with three blades because of greater gyroscopic balance and less strength requirements from gearbox. They are aerodynamic with an aircraft wing-like profile and typically made from fiber-glass [28].

The **rotor hub** is the central part that all the blades are connected to. It transports the rotational energy to the rotor shaft. The rotor shaft is fixed to the hub. The shaft is then connected to the gear box.

The **gear box** function is to increase the low rotational speed of the rotor to the high speed of the generator shaft that is required for efficient operation. However, gearless turbines are also available which combine compact structure, easy maintenance and lower chance of breakdowns. Additionally, a **control system** secures the safe operation of the system (e.g. avoidance of high speeds that could lead to damage). Pitch control and stall control are its main functions. Also, a **rotor brake** is included to prevent the rotor motion whenever necessary (e.g. during maintenance).

The high-speed rotating **shaft** of the generator converts the rotational energy into electric energy. This is done via the electromagnetic induction. The generator may be asynchronous (aka induction) or synchronous. Most wind turbines use asynchronous generators to produce alternating current that is fed into the grid through a step-up transformer.

The **nacelle** is a structure upon the tower that connects to the rotor hub and houses the aforementioned components: the rotor shaft, the rotor brake, the gear box and the generator. The nacelle is capable of rotating so that the rotor axis is always aligned to the wind direction. The rotating mechanism is called “yaw system”.

All these components within the nacelle are supported at a high elevation on top of a **tower** structure. The factors that determine the height of the tower is the rotor diameter and the wind conditions of the site. Their construction material is steel tubes and house electric cables, control systems, and a ladder or a lift for maintenance purposes.

The **control system** monitors and collects operational data, controls the turbines and allows remote communication with the operators. Among others, these controlling functions include the control and monitoring of the rotational speed, the yaw direction, the voltage and current levels, the vibration frequency of blades and nacelle. Also, weather condition data are collected.

Finally, a **transformer** is placed near the tower on the ground and increases the generator's voltage to the appropriate voltage rating depending on whether it is connected to the high voltage (transmission system) or to the medium voltage (distribution grid) in case for small farms or individual turbines [28].

2.3.2 Solar

Solar energy sources harness the inexhaustible energy from the sun. Solar energy is the most abundant and powerful source of energy. It provides vital energy to plants and powers the wind and the weather on the planet. Solar is a variable RES due to the day-night cycles and intermittent due to the clouds.

In just one hour more sunlight energy hits the earth than is used by humans in one year. The amount of solar energy on an annual base is 10,000 times more than the global energy requirements [32]. So, even the available Power Conversion Efficiency of twenty per cent is enough to provide for the world energy demand if only the 1‰ of the earth's surface area is covered by PV systems.

As of 2021, the 6 countries with the highest solar PV capacity in decreasing order are China (307TW), the USA (95TW), Japan (74TW), Germany (58TW), India (50TW), and Italy (23TW). As far as Greece is concerned, the solar PV capacity was 3,530 MW in 2021 [26].

The main solar technologies are a) the solar photovoltaics, b) the passive solar and c) the solar water heating for homes and businesses.

The solar photovoltaics technology is one of the most important RESs and most rapidly grown worldwide today along with the wind. Utilities, businesses, the industry as well as individuals use solar photovoltaics technology to produce electricity.

Solar Photovoltaic Technology

Solar cells (aka "photovoltaic cells") can turn sunlight into electricity. The solar-electric cell is the smallest part of a silicon semiconductor that can generate electric current when it is exposed to light.

Photovoltaic (“PV” for short) takes its name after the photovoltaic effect that is the process of converting the sun light (i.e. photons) to direct current (i.e. electricity). This phenomenon was first detected by accident in 1954 during experiments on semiconductors. In particular, the silicon semiconductors with impurities generated electric current when exposed to direct sunlight.

Solar cells are used in arrays as a means to power various devices (e.g. space satellites, calculators, watches etc.). Today, electricity from solar cells is a commonplace since it has become a cost competitive technology during the last decade in many regions. Large-scale deployment of solar parks is increasingly taking place worldwide to help power the electric grid.

The cost of PV systems per installed kW has been considerably reduced by 70% from 2010 to 2020 according to NREL [33, 34]. Specifically, from 2010 to 2021, there has been a 64% reduction in the cost of solar PV systems and a 69% of roof-top systems and a staggering 82% reduction in the cost of utility-scale PV systems [33, 34]. Nowadays, the cost is less than one third of what it used to be 10 years ago. Apart from being affordable, it is a durable and low-maintenance technology.

Solar photovoltaics work during the day when there is sunlight and are ideal for sunny climates. Without sunlight no electricity is produced unless storage devices are used to store the excess energy (i.e. more than the current demand) when sunlight is available and supply the stored energy back to the grid when needed.

Silicon Solar Cells

Nearly all solar cells that are commercially manufactured today are made from silicon and are relatively cheap while offering good efficiency (i.e. the rate at which sunlight is converted into electricity) [36]. These silicon cells are assembled into bigger modules called “panels” and in this way can be easily installed on rooftops or deployed on racks on the ground to create large systems that are in turn connected to the distribution power network or the transmission grid for utility-scale systems (capacity > 10MWp).

However, other technologies are also available but not as popular as the silicon solar cells. These technologies include among others:

i) the thin-film solar cells that are flexible, lightweight and require less energy to manufacture,

ii) the III-V solar cells that are made from group III and V elements of the periodic table (e.g. indium and arsenic, antimony and gallium) and exhibit high efficiency sunlight to electricity conversion rates at the expense of costly manufacturing techniques, and

iii) solar cells constructed of organic materials and hybrid inorganic/organic substances (aka "perovskites") that promise to produce low cost, easy to manufacture solar cells.

Solar cell working principle – Photovoltaic Effect

A solar PV cell is an electrical equipment that converts the sunlight energy into electricity via the PV effect. When a PV cell is exposed to light, a small voltage or electric current is generated. A solar cell is a special junction of p-n diode whose electrical properties are determined by the energy of the incident light rays. Such electrical properties are current, voltage and resistance.

Its construction consists of a slim layer of n-type semiconductor placed above a thick p-type semiconductor with a p-n junction between them [36].

The incident light photons can easily reach the p-n junction through the thin n-type layer. The light photons that are hitting the p-n junction provide with enough energy to create electron-hole pairs. The equilibrium of the junction is disturbed and the depletion zone electrons move towards the n-type layer as can be seen in Figure 2.7. On the contrary, the holes move to the p-type layer of the diode. Thus, the p-n junction behaves like a tiny battery exhibiting a potential difference (i.e. voltage) between the two ends [36]. If a load is connected, then a tiny current will flow through it.

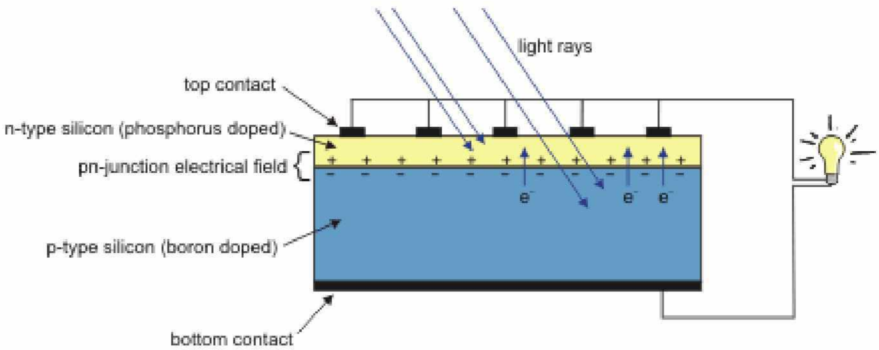


Figure 2.7 PV cell structure and principle of operation (source: www.lrc.rpi.edu)

In practical application, the PV diode is enclosed by glass for mechanical stability and protection purposes.

In Figure 2.8, one can see the characteristic curve of the V-I (which are the independent variables of voltage and current) as a function of the connected load to the circuit, with one end denoting the open circuit (infinite resistance) and the other the closed circuit (zero resistance) [36].

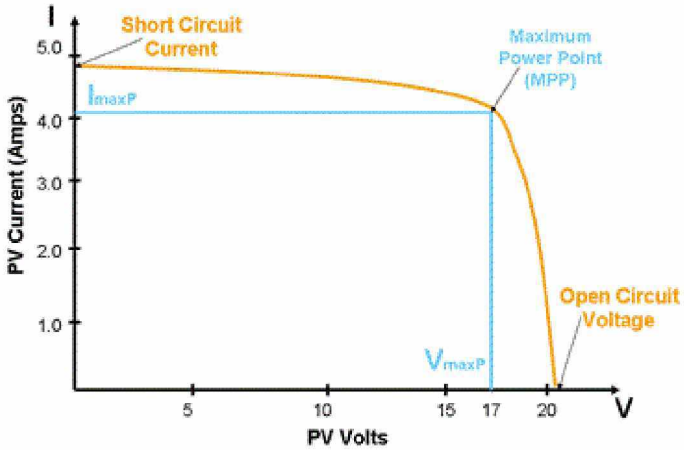


Figure 2.8 Pholtovoltaic Cell V-I characteristic (source www.electrical4u.com)

PV efficiency limit

The efficiency of a photovoltaic p-n junction was evaluated by Shockley and Queisser in 1961 [37]. The efficiency limit of an ideal single-junction solar cell of 1.3eV bandgap is 33.7% [38], known as the Shockley-Queisser (SQ) limit.

The PV power conversion efficiency (PCE) is rather low as compared with other renewables. PCE of 20% is commercially available in modern PV systems. Nevertheless, a record of 26.7% has been achieved for crystalline silicon solar cells.

The following Figure 2.9 shows the theoretical Shockley-Queisser limit as a function of the bandgap and also the efficiency for various technologies [35].

The optimal efficiencies are shown for different materials; hexagons refer to crystalline materials, the circles refer to thin photovoltaic film and the stars refer to new technologies.

The first semiconductor material used for solar cells was silicon. However, many other materials are currently used, including inorganic semiconductors as well. All these PV cell technologies are named after the light-absorbing material. These technologies come in two main categories, namely, the wafer-based and the thin cell films.

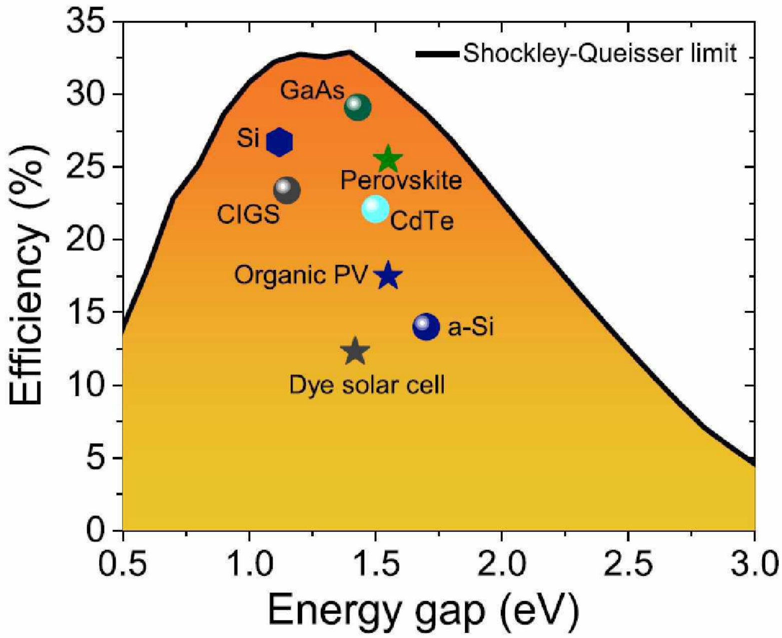


Figure 2.9 Theoretical Shockley-Queisser efficiency limit (black line) [35]

Concentrating Solar Power

It's worth referring to the Concentrating Solar Power (CSP) as an interesting emerging technology because it combines solar energy with storage energy in the form of heat. Concentrating Solar Power systems exploit heat from sunlight in order to produce electricity.

Although traditionally power plants used fossil fuels as a source to boil water, nowadays they can alternatively use concentrating solar power systems. In essence, the boiling water spins a turbine which in turn drives a generator that produces electricity [39, 40].

The main types of concentrating solar power systems are a) the power tower, b) the linear concentrator and c) the dish/engine.

a) Power Tower. This system comprises of many flat mirrors that are tracking the sun (also known as heliostats) and focuses the light to a receiver on top of a tower, as illustrated in Figure 2.10, thus achieving a great concentration of light otherwise impossible to accomplish. Then, the concentrated light heats a heat-transfer fluid and the produced steam spins a conventional turbine that drives an electricity generator. In the simplest case, the heat-transfer fluid is water whereas in more advanced cases, special molten nitrate salt is used due to its excellent heat-transfer and thermal storage properties. The high energy storage capabilities of the nitrate salt allow for energy storage and delivering it during the night or cloudy weather during the day.

This technology combines solar renewable with storage thus providing dispatchability [39, 40].

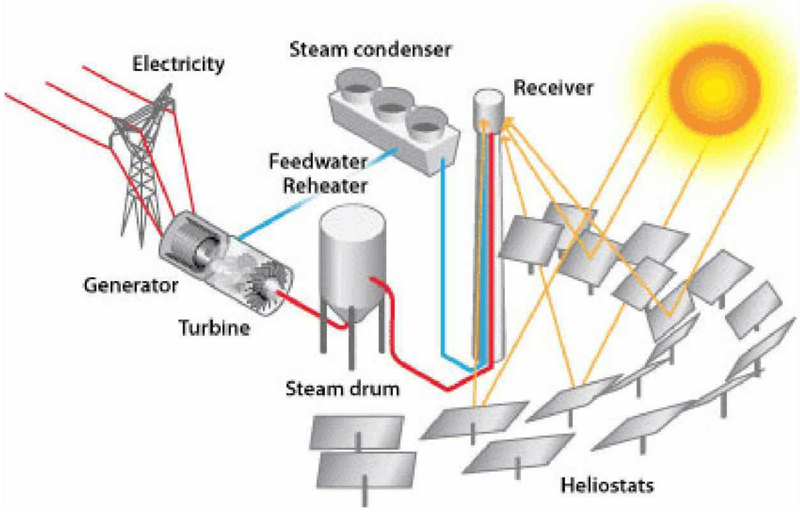


Figure 2.10 Schematic representation of a Power Tower system with heliostats [41]

b) Linear Concentrator. This system captures the sun's energy by means of long rectangular mirrors that focus the sunlight to a receiver tube. Usually, they are used in arrays of many parallel receiver tubes. As shown in Figure 2.11, the concentrated sunlight heats a heat-transfer fluid which flows in the tubes. Similar to the aforementioned type, the heat-transfer fluid is used to spin a conventional steam turbine generator system to ultimately provide with electricity [40, 41] as illustrated in Figure 2.11.

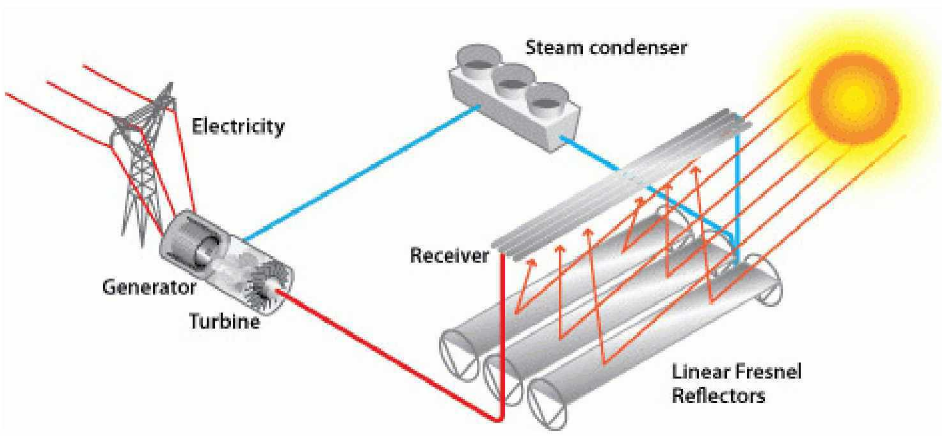


Figure 2.11 Schematic representation of a Linear Concentrator solar system [41]

c) Dish / Engine. The dish-engine system uses a parabolic mirror (similar to a satellite dish) or a parabolic structure of many small flat mirrors to reflect the sun light and concentrate its beams onto a thermal receiver which absorbs heat and transfer it to an engine generator. This CSP (concentrating solar power) system produces lower electricity power that the other CSP systems (typically up to 25kW) but is appropriate for modular use. In the following Figure 2.12, one can notice that it consists of two components, namely the solar concentrator and the power conversion unit.

The former is the dish structure that is constantly tracking the sun during the day for maximum sunlight concentration to the thermal receiver. The power conversion unit consists of a thermal receiver and an engine/generator system. The thermal receiver collects the beams and the solar energy converted into heat. Then the heat is transferred to the engine/generator system. The thermal receiver is usually an array of tubes filled with a fluid that can easily transfer the heat, such as hydrogen or helium. The engine-generator subsystem acquires the thermal energy from the thermal receiver and converts it into electricity.

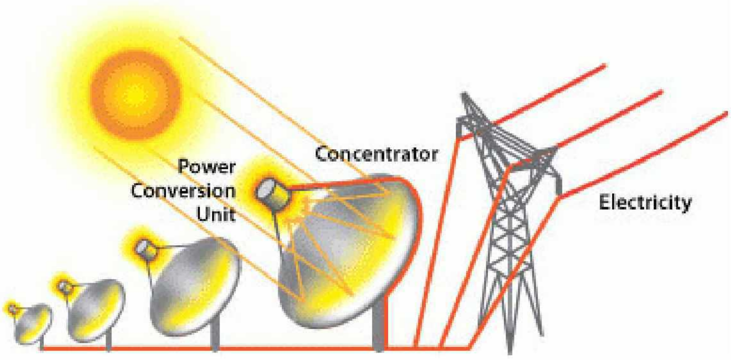


Figure 2.12 Schematic representation of a "Dish/Engine" concentrating solar system [41]

Reliability and Grid Integration Research

Current PV research is concerned not only with high efficiency solar cells and low-cost panels, but also with long-term durability and reliability of electricity generation. Over time, the electricity generation performance decreases. Minimizing the performance degradation is another technological challenge that PV research attempts to tackle with [35].

Utilities, government regulators and policy makers aim to achieve ever higher levels of solar and wind penetration. Unfortunately, wind and solar are variable sources, so it's a challenge to keep the grid stable without disturbing the sensitive balance between electricity supply and demand, and also keeping the frequency and voltage levels unaffected [35].

Cost efficiency and LCOE

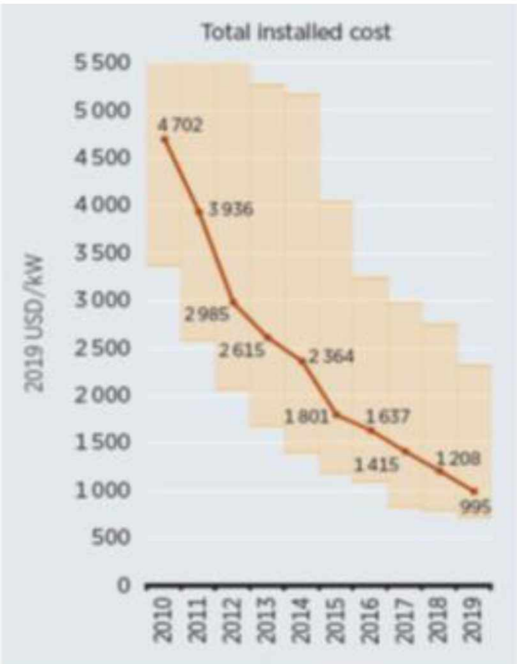
The use of the photovoltaic effect is the most efficient and most popular method to transform solar energy to electricity. Until the beginning of the decade of 2010, the high cost was the main limiting factor for PV expansion with regard to fossil fuels electricity generation cost. The power generation cost is an important factor for all renewables when the issue of energy transition is considered.

However, the economies of scale in increased production capacity along with the enhanced performance achieved by modern PV systems have significantly lowered the cost of solar energy supply roughly 80% in the decade from 2010 to 2019 as shown in Figure 2.13. In particular, the installation cost has fallen below 1,000$/kW (Figure 2.13a) with the cost of solar panels as low as 0.3$/Wp [35]. A common way to compare various energy sources is the use of the so-called Levelized Cost of Electricity (LCOE). The LCOE is defined by the formula that follows:

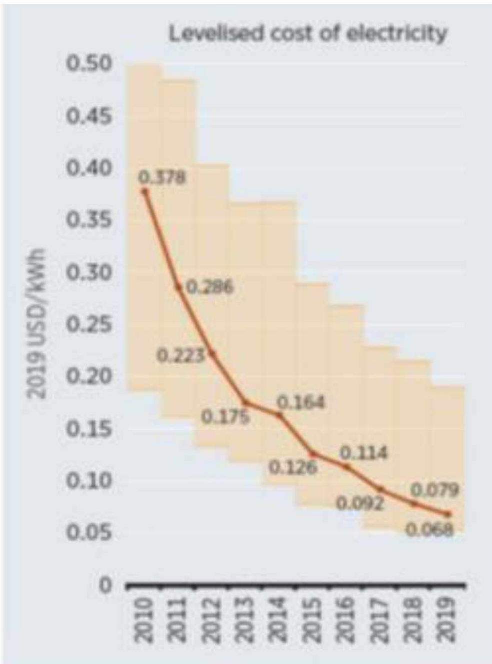
$$LCOE = \frac{CAPEX+OPEX}{Yield}$$

where CAPEX is the capital expenditure, that is, the initial investment that comprises the components cost, the labor and other extra costs. OPEX is the operating expenditure which comprises the costs of utilization, maintenance and taxes. Finally, Yield is the total amount of energy production that the system acquires during its lifetime. In simple terms, the LCOE is an estimate of the electricity generation average cost of a generating plant throughout its lifetime and it is measured in $/kWh.

The average LCOE of solar energy is decreasing rapidly since 2010, as shown in Figure 2.13b.



a) Total installed cost



b) Levelised cost of electricity

Figure 2.13 PV total installed cost and levelized cost of electricity from 2010 to 2019 [42].

These LCOE values depend on PV technology used, the total power installed and the solar resource potential (global irradiation, kWh/m^2) of the particular place. The global average of LCOE is 0.068 $/kWh, ranging from 0.050 to 0.180 $/kWh. In sun-rich places the cost can be even lower reaching values as low as 0.020 $/kWh [35]. Such low LCOE values make solar RES equally competitive to conventional fossil fuel energy sources with LCOE ranging from 0.043 to 0.150$/kWh.

Hydropower

Hydroelectric power (aka hydropower or hydro) is an old and mature technology to generate electricity. Hydropower uses the natural flow of water stream to generate electricity. It is a cost competitive technology and the oldest renewable energy source available, which generates large amounts of electricity accounting for 16% of global electricity production [43].

The hydropower plants can be classified in three main types as follows:

- Conventional (or Storage) hydropower:

  A conventional hydro plant comprises of a large a dam used to store water in a reservoir. When water streams are released from an elevated reservoir to a turbine which activates an electric generator and then electricity is generated. Such plants can provide both base load and peak load since the reservoir can be large enough to be used for long periods of time. Also there is the ability to start up and shut down their power much faster than gas turbines (i.e. in less than a minute) or to fast increase and decrease their output (i.e. fast ramp-up rate). This characteristic is providing responsive power that is needed to integrate renewable energy. It is typical for conventional dam plants to have a storage capacity that enables them to operate independently for many weeks or months even if there is no water inflow [43].

- Run-of-river hydropower:

  It is a facility that uses the flowing stream of a river in order to turn a turbine. Generally the run-of-river facilities have limited or no storage capability. Such systems can provide electrical energy as a base load, and also flexible operation capabilities for variations during the day by regulating the water flow [43].

- Pumped storage hydropower:

Pumped storage hydropower transfers amounts of water from the lower reservoir to the upper one by means of pumps when there is energy surplus in the power system or in periods of low demand. When renewable energy production is not enough to meet the demand or when the energy demand is high, then water stream is released again from the upper reservoir to the lower one via turbines thus balancing the electrical production with consumption energy.

These technologies can also be used in combination. So, there are cases where the storage facilities involve water pumps to replenish the natural water in the reservoir and there are run-of-river plants accompanied with storage capability.

It’s worth noting that Norway is the undisputable champion of hydropower. Norway has successfully harnessed its abundant hydro potential since its hydroelectricity accounts for about 98% of the total generation. In recent decades renewable generation from wind and biomass was also added. Fossil fuels cover only a minimal amount of its supply.

2.3.3 Ocean and Tidal Energy

Ocean energy (also known as wave energy) is energy derived from harnessing the

Tidal energy is a renewable source of energy which harnesses the move of ocean water between the high and the low tides.

Tidal or offshore hydropower is the least established technology that uses tidal surges or wave power to generate electricity at sea. Tidal energy production technology is considered to be in infancy, although in recent years, a double-digit growth has been witnessed in respective technologies in terms of power capacity installed. Wave height and frequency determine the energy of the wave.

There have been developed methods to use tidal movement for electricity generation in marine areas of significant tidal capacity. The tidal range is the distance between the high and the low tide.

Wave Energy technologies

There have been developed various wave energy technologies. Wave height and frequency determine the total wave energy that can be extracted. Among others, there are four main technologies, namely: Absorbers, Attenuators, Inverted-Pendulum, and Oscillation water columns [44].

- Absorbers capture the energy of the wave rise and fall by using a floating buoy. The captured energy is transformed to electricity by a generator.
- Attenuators capture the wave energy by being placed across the waves. This way the connected attenuator segments bend and stretch, and the oscillatory motion is transferred to hydraulic pumps which transform the energy into electricity.
- Inverted pendulum equipment uses the waves motion to oscillate a hinged pendulum. The motion of the inverted pendulum is attached to a hydraulic pump that drives in turn an electrical generator [45].
- Oscillating water column devices are partially submerged enclosed structures that use wave movement to pressurize air in a chamber and then channel it into an air turbine. Specifically, the upper part (above the water) is full of air and the waves coming from the bottom make the water to rise and fall. Thus, the air column is pressurized and depressurized respectively. Due to the fluctuating pressure, the air is pulled and pushed through an air turbine at the top of the structure. The air turbine is in turn coupled to a generator to produce electricity [46].

Tidal Energy technologies

There are three main technologies to use ocean waves and tides for energy generation:

- Tidal streams. It is a fast-moving stream due to the tide effect. Water turbines are placed in tidal streams in the sea to capture the tidal energy of the water flow. In contrast to wind which is variable; tides are predictable and stable. The electricity produced by tides is steady, rendering tidal streams a reliable renewable energy source.

- Tidal Barrage. This technology harnesses the tidal potential energy. Tidal barrages (i.e. large dams) are usually built across a bay or an estuary. The specific installation site is carefully chosen so as the tidal range is more than 5 meters [47]. There are only 40 such appropriate locations around the world as shown in Figure 2.14.

As seen in Figure 2.15, there are special ocean turbines inside the barrage exploit the tidal power. During the tidal rise, the barrage gates are open. At the point of the highest tide, the barrage gates are shut in order to create a tidal lagoon. Then the water is left to flow through the barrage turbines and electricity is generated in a controlled manner.

Figure 2.14 Appropriate sites for harnessing tidal energy [95].

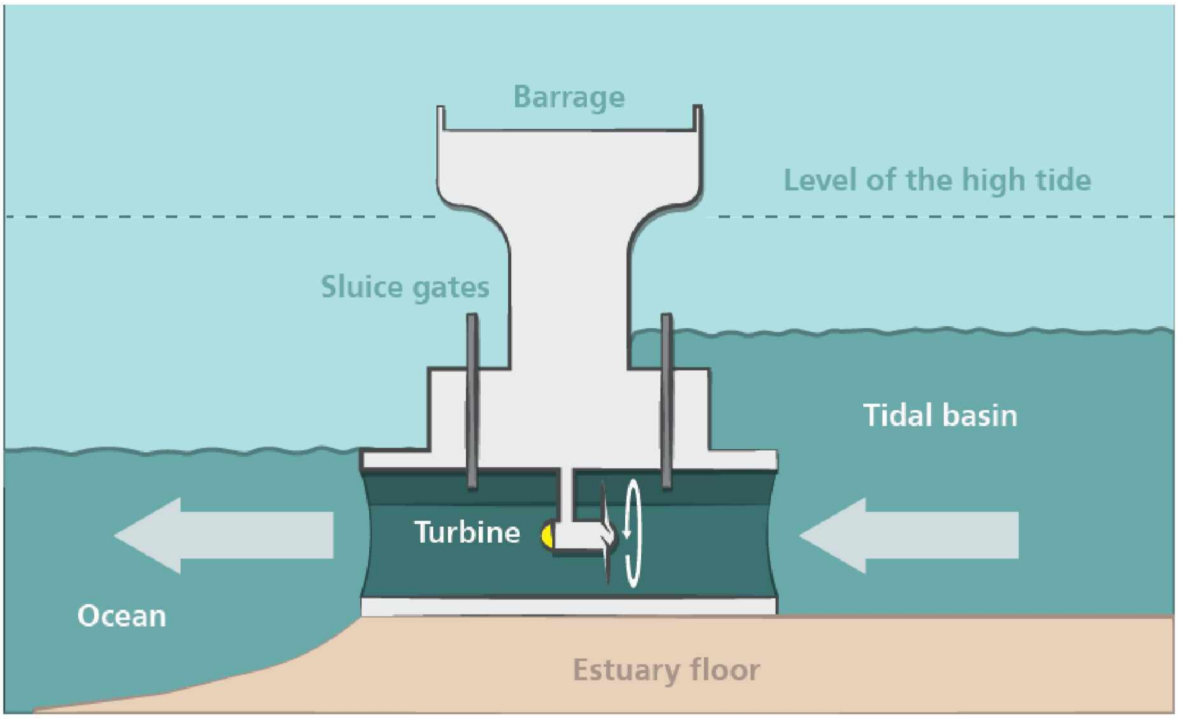


Figure 2.15 Tidal Barrage system diagram [107]

However, this technology comes at an environmental cost as the flora and fauna are significantly affected.

- Tidal Lagoon. This technology involves the construction of tidal lagoons. Tidal lagoons are ocean areas that are partly enclosed by natural and/or artificial barriers. A tidal lagoon energy generator operates in a similar way to a tidal barrage although the former generate power continuously while the lagoon is filling and emptying whereas the latter rely on the high and low tidal periodicity. The tidal lagoon environmental impact is low and so is the electrical power generated [48].

2.3.4 Geothermal

Geothermal energy is essentially the earth’s heat. Geothermal energy was traditionally used for heating buildings as well as for bathing. Nowadays, it is also used to generate electricity.

The etymology of “geothermal” derives from the greek words for earth (“geo”) and heat (“thermal”). It is a renewable energy source because heat is constantly released from within the earth.

There are a few technologies that have been developed to harness the earth’s geothermal energy.

- Steam reservoirs or hot water that can be accessed by drilling deep into the earth,
- Geothermal reservoirs that are located on the earth’s surface,
- The shallow ground under the surface of the earth that keeps a relatively constant temperature of around 13°C.

These geothermal resources exist in both small and large scales. The hot or warm water and steam from reservoirs can be used by Utilities to move turbines which in turn drive generators and consequently supply electrical energy. Alternatively, the produced heat is directly transferred to buildings, homes, factories etc. for various uses [49].

It's worth noting that Iceland is the world pioneer as far as geothermal energy is concerned. Geothermal energy sources are abundant and have been exploited for both electricity generation and space heating. Electricity generation has considerably increased in recent years, accounting for more than 25% of the country’s electricity supply [50].

GE is still an unexploited sustainable and renewable energy. It is an environmentally friendly resource with a lot of future potential not only in electricity production but also in heating and cooling.

Apart from the numerous advantages, the geothermal energy faces various challenges that must be tackled so that this renewable resource is fully harnessed [51, 52].

Advantages

Following are the main advantages of GE.

- GE is environmentally friendly since its carbon footprint is much lower than the pollution associated with fossil fuels.
- GE is renewable and sustainable because the hot reservoirs in earth are replenished naturally.
- There is great potential for future growth and adoption. Currently, the GE share of electricity production is minimal. Ongoing research and development are expected to render many geothermal resources exploitable. Geothermal power could potentially provide up to 2 TW of power.
- As opposed to solar and wind power, GE provides a reliable and stable energy source which is always available, programmable and its power production is easily anticipated.
- In addition to the electricity generation, GE can also be used for heating and cooling. A geothermal heat pump can effectively use the difference between the ground temperature and the surface temperature, with the former acting as source or heat sink in order to provide heating or cooling respectively.

Disadvantages

Apart from the many benefits and advantages, the Geothermal Energy (GE) is also associated with some environmental, economic, social impacts and technological challenges that need to be addressed.

- Location restrictions. The main disadvantage of GE is the fact that it is site-specific. GE facilities need to be constructed at locations where the geothermal sources are available, that is, many other places are excluded from GE exploitation.
- Gas emissions. GE plants do not release GSGs directly but the process of digging into the earth causes the underneath stored gases (e.g. CO2, H2S, NH3 and CH4) to be released into the atmosphere in the form of oxidation products such as SO_2 and NO_x, albeit at a greater rate than the otherwise natural release. Nevertheless, these GHG emission close to GE plants are much less severe than those caused by fossil fuels.

- Expensive. GE plants are expensive to build, with cost ranging from more than $2 up to $7 million per 1MW power capacity. Although the initial costs are high, the long-term investment is profitable.
- Geological hazards and earthquakes. The process of GE digging under the surface of the earth can additionally result in structure changes which can cause land subsidence and earthquakes. Specifically, the extraction of geothermal fluids decreases the pressure under the crust and the rocks move to a deeper level so that the crust moves downwards (land subsidence). This is especially the case with geothermal technologies that use high pressure water to open fissures into the earth's crust. This process facilitates further the exploitation of the geothermal resource but results in more structure alterations that increase the possibility of earthquakes.
- Sustainability. Another challenge to be sufficiently addressed is the sustainability issue of the GE fluid. After its release, it must be forced back into the reservoir at an equal as that of its depletion. Thus, the issue of proper management and stability maintenance is of great importance [52].

2.3.5 Biomass & Biogas

Biomass

The term "biomass" refers to the organic materials that come either from plants or animals, and also from matter derived via natural or artificial transformation such as decay, fermentation etc. [53, 54]

Biomass is a natural resource that exists in various materials such as wood, manure, saw dust, seed, paper, household waste etc. Biomass was always used by humans and nowadays their use is increasingly even more important because it can facilitate the green energy transition. The global agricultural production creates huge amounts of by-products that can be utilized as a significant energy resource, also known as energy crops [55].

Biomass material is derived by plants and animals waste that can be used as a fuel to generate electricity and/or heat. For example, industry, farm and household waste are considered biomass. Additionally, agricultural residues, energy crops and wood (also wood residue) are appropriate biomass fuels. There is a slight difference between the terms "biomass" and "biofuel", although they are used interchangeably when the biomass can be used directly as a fuel, as in the case of wood.

Biofuel is a term to denote the fuel that is derived from biomass after appropriate processing. Firewood, wood shavings, pellets, nutshells and fruit stones are examples of biomass used to produce biofuels. The use of firewood usually does not involve any process and, more often than not, it is used directly. On the other hand, pellets require a special process before they are ready for usage. Fruit stones, seeds and fruit husks, are increasingly used as solid biofuel with a high heating potential similar to other biofuels [56, 57]. The increasing production of such by-products renders them popular to energy production since they contribute to the reduction of GHG emissions as compared with fossil fuels [55].

Biogas

Biogas is a mixture of gases, produced from unprocessed matters, for example, agricultural and municipal waste, plant material, food waste, manure and sewage. The mixture of gases consists mainly of CH_4 (methane), CO_2 (carbon dioxide) and H_2S (hydrogen sulfide), along with moisture and siloxanes. Biogas is a renewable energy source.

The production of biogas involves the anaerobic digestion with methagens (anaerobic organisms) inside a biodigester.

Biogas can be burned (i.e. oxidized) with oxygen. The energy released makes biogas a suitable fuel. It can be used either in fuel cells or for heating purposes (e.g. cooking).

By means of a gas engine, the biogas energy can be readily converted into electricity and heat.

Liquid, solid or gaseous biofuels can be produced by many agricultural crops and their residues. For example, the process of the anaerobic digestion is used to convert biomass into biogas. Also, digestate is produced as an output by-product which is the remaining material of the biodegradable feedstock [58].

The perennial crops seem to be the most promising for bioenergy and biogas production. This is due to the fact that perennials can be harvested for many consecutive years without the need of annual sowing and give high biomass yield without quality degradation. The aim of anaerobic digestion of perennial grasses is to achieve as high biogas productivity as possible [58].

Renewable energy sources such as bioenergy, geothermal and hydro can be instrumental to reducing the GHG footprint only in a modest proportion because the current and future energy demands are so high that the contribution of wind and solar is necessary to practically meet the global energy needs [57].

Biogas can considerably contribute to the reduction of GHG emissions if good practices are used and efficient systems are implemented. Therefore, better technics and more efficient systems are still to be developed and employed. This can be instrumental in promoting sustainable development and improving people's livelihood and health [57].

Biogas reactor working principle

The working principle of a biogas plant is the anaerobic digestion or fermentation of biomass as shown in the following Figure 2.16 where the reactor has an underground structure.

Initially, the biomass is mixed with water and then it is decomposed by the methagens (i.e. anaerobic organisms) into gaseous products such as methane, hydrogen, carbon dioxide etc. and digestate as a by-product. Digestate is the residual material after the anaerobic digestion that can be further used as fertilizer.

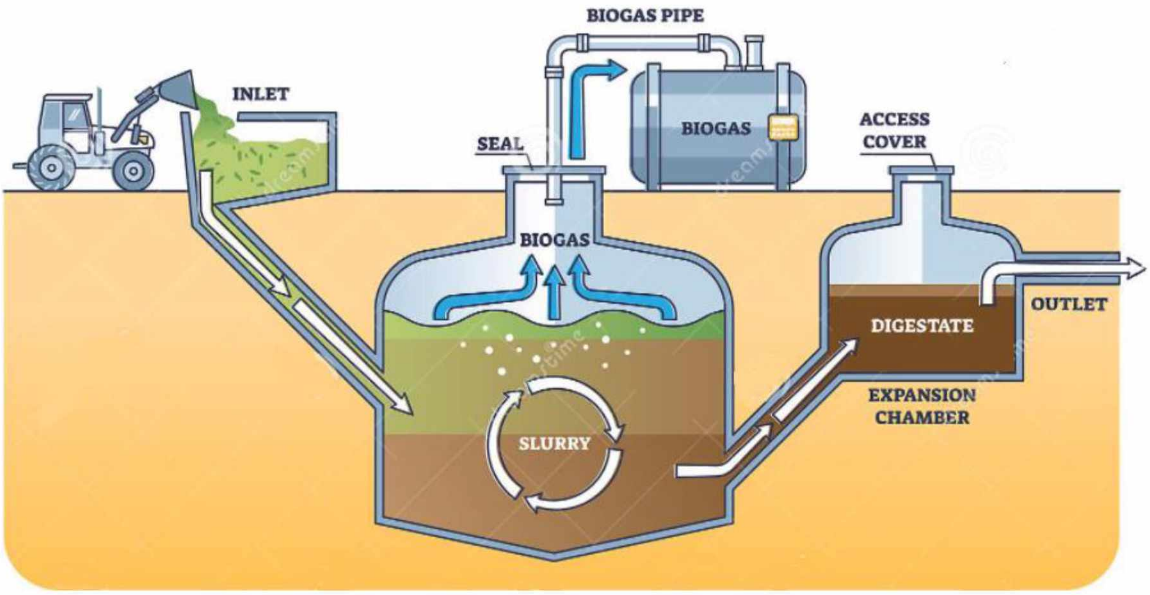


Figure 2.16 Biogas reactor diagram of working principle (source: dreamstime.com)

In the above diagram, the input of the biogas plant is the mixing tank where the biomass is mixed with water to form the slurry. Then the slurry enters the digester tank in the middle of the diagram where it is stirred and fermented at the appropriate temperature. The digester is an airtight chamber without oxygen (anaerobic). By adding microorganisms (anaerobic bacteria), the biomass is decomposed, that is, its complex organic substances break down into basic inorganic gases such as methane, hydrogen, carbon dioxide and hydrogen sulfide. The produced gases are stored in a gas tank. The remaining solid substances are stored into the expansion chamber. These substances constitute the so-called digestate (manure, fertilizers).

The biogas that is produced in these plants, can be used as a fuel (e.g. in gas engines) and as a kitchen gas, thus providing many commercial and household applications.

Advantages of Biogas

- Eco-Friendly. It is a clean and renewable source of energy. The bio-digestion process is producing gases that are non-polluting. It even reduces the GHG emissions into the atmosphere since no combustion takes place during its generation. Moreover, the feedstock used for biogas production is renewable. Crops (along with their residure) and trees will always be available as well as manure and food scraps, thus rendering biogas a sustainable alternative.

  Therefore, biogas is a way to combat climate change and to lower the reliance on fossil fuels [59].

- Reduction of water and soil pollution. Landfills give off undesirable smells but most importantly are the sources of toxic chemical substances draining down to water aquifers. When biomass is utilized for biogas production instead of dumping it in landfills, we can prevent soil and water pollution. In addition, pathogens and parasites are deactivated by anaerobic digestion, thus effectively reducing waterborne diseases. Wherever biogas plants exist, the collection and waste management have improved, so that environmental and sanitation issues have diminished [59].

- Fertilizers. The by-product of the anaerobic fermentation is a rich in organic substances digestate suitable for usage as a fertilizer substituting their chemical counterparts which have toxic effects [59].

- Simple and low-cost technology. The biogas production technology is relatively cheap and easy to install. The initial investment is modest and the gas produced can be used directly for electricity generation through a system of a coupled gas engine with an electricity generator.

Disadvantages of Biogas

- Few Technological Advancements. Unfortunately, the systems used for biogas production systems are rather inefficient. New technologies are needed to make the process more efficient and further bring down the cost. There is limited interest by the governments to invest in the sector.

- Impurities. The produced biogas contains impurities that render it inappropriate for certain uses. For example, it would lead to metal corrosion if it were to be used in automobiles.
- Temperature impact on production. The weather in general and the ambient temperature in particular can have unfavorable impacts on biogas production as is also common on other RES (e.g. solar, wind). The optimal temperature for anaerobic bacteria to maintain the digestion process is about 37°C. In case of cool climates, the digestion process needs extra energy to keep the optimal temperature and sustain a constant biogas supply.
- Unsuitable for densely populated areas. This is another disadvantage because biogas plants require large quantities of raw materials (e.g. manure) that usually are hardly available in densely populated metropolitan areas. This is the reason why biogas generation is appropriate for suburban and rural areas where the feedstock needed may be plentiful [59].

2.3.6 The special case of Nuclear Energy

By any rigorous definition, nuclear energy is not renewable. But Nuclear Energy is generally considered clean since it does not release GHGs, thus rendering it a low-carbon fuel and unconducive to climate change. Hydropower is the largest source of low-carbon electricity but Nuclear Energy is the second largest [60].

Due to the above arguments, many researchers find nuclear energy appealing and consider it a promising technology to fight climate change and reach the 2015 Paris Agreement goals.

Nuclear power is admittedly a zero-emission energy source that is usually omitted from the list of the other conventional clean energy sources. It’s worth noting though that nuclear is second only to hydropower regarding the low carbon electricity worldwide.

The nuclear technology generates electrical power through fission, that is, the splitting of uranium atoms that release energy. The released heat energy creates steam that turns a turbine which drives an electrical generator. The produced electricity is devoid of any of the harmful byproducts related to electricity generation by fossil fuels. By keeping the air clean, nuclear power inhibits the emission of thousand tons of GHG’s that would otherwise exacerbate harmful conditions such as acid rain, lung cancer and coronary heart diseases among others [61].

Another advantage of nuclear is that its waste is minimal because the nuclear fuel is very energy dense. Furthermore, the nuclear waste reprocessed and recycled.

However, Nuclear Energy is not renewable. In order for a source of energy to be considered as renewable, its source must be constantly renewed, that is, it is not exhausted but replenished automatically and it can therefore remain a viable energy source for many generations to come. Wind and solar energy are examples of sustainable energy sources since humans cannot deplete neither solar nor wind energy. Light energy produced by sun is practically inexhaustible and the earth rotation will keep generating wind for as long as human civilization exists.

Scientists disagree about the classification of nuclear energy with regard to sustainability. Nuclear energy does not renew itself, however — once it is used up, it is gone as well.

Nevertheless, it is not possible in practice to consume all the nuclear energy available and deplete the nuclear resources over the scale of human existence as is the case with fossil fuels.

An energy source is considered to be renewable when its resources can be constantly replenished. For example, the water of the hydroelectric dams is replenished by rain and flowing water streams, and the sunlight is available every day for the solar panels. In that respect, nuclear energy is not renewable since the radioactive fuel is not replenished after it is used up [60].

Nevertheless, there are ongoing research efforts to make nuclear energy practically renewable. Instead of using mined ore to extract U-235, sea water could be an alternatively option.

It's worth noting that uranium extracted from seawater is continuously replenished, so nuclear becomes as renewable as solar, wind and hydropower [62].

As a totally abundant resource, the sea water can make the nuclear power practically renewable. Theoretically, the 4 billion tons of sea water uranium would be able to fuel a thousand nuclear plants of 1GW capacity for a hundred of millennia. Uranium nuclear fuel derived from seawater was traditionally not economically feasible. Although, new technological breakthroughs are promising exactly that [62].

Advantages of Nuclear

There are no GHG emissions during the operation of the nuclear plants. In the course of their life cycle, they produce similar amounts of GHG emissions (per power unit) to wind and only one third with respect to solar power [63].

Many researchers and scientists believe that nuclear power has an essential role to play in the next decades if the 2015 Paris Agreement targets are to be reached and climate change to be successfully averted. The reason is that the renewable energy capacity that is available is not yet enough to satisfy the total energy demand [60].

Moreover, solar and wind power are intermittent although nuclear power is constantly operational, although intermittency could be alleviated in the long term by energy storage which in turn requires extra capital expenses.

Disadvantages of Nuclear

Apart from the positive role nuclear can play due to its particular favorable characteristics, one should not disregard its disadvantages as well. The most prominent among them that raises public awareness, is the radioactive waste and its treatment.

It must always be transferred in a safe manner to special storage sites where will be reprocessed and kept in isolation for thousands of years if necessary, so that it poses no health hazards to humans or any environmental risks. There are ongoing research efforts to minimize the impact of these threats [60].

In a nuclear power plant, the process of nuclear fission is harnessed. That is, to split the nuclei of uranium atoms apart to smaller nuclei. During the nuclear fission a great amount of energy is produced from a small amount of uranium-235. The total supply of uranium in the world is limited and it cannot be renewed after the fission. This is why nuclear energy is not a renewable resource.

But, although fossil fuels reserves are going to be depleted in the foreseeable future, the nuclear fuel reserves are not expected to be depleted for many human generations in the future.

Nuclear Reactor Technologies

A nuclear reactor is a system that can start and maintain a self-sustained nuclear fission. Nuclear reactors are utilised (among others) for producing energy in the form of electricity.

The principle of nuclear fission is used by nuclear reactors. In essence, a large and heavy nucleus is split to smaller nuclei. These atomic fragments are emitting neutrons, photons and other particles because they are in a high energy state. The emitting particles can start new fissions. The new fissions may in turn emit more particles and so on. If this process is self-sustaining then the series of fissions establishes a "fission chain reaction". The amount of energy released by a chain reaction is large and this is the base of nuclear power plants.

The nuclear power reactors provide the heat required to drive steam turbines that ultimately run electric generators.

There are several types of nuclear power reactors as follows:

- Light Water Reactor Technologies

  The Light Water Reactor (LWR) is the most popular technology. It is a type of thermal neutron reactor that utilizes ordinary water. Other technologies opt for "heavy water" which contains larger quantities of deuterium isotope and that's why "heavy water" is a better moderator. Normal water is known as protium because it consists of hydrogen-1 isotope. LWRs use water not only as a coolant but also as a neutron moderator. The role of neutron moderator is to decelerate the speed of neutrons. The nuclear fission is always controlled and results in producing heat [64].

  There are two main reactor types: a) the Pressurized Water Reactor and b) the Boiling Water Reactor. In the Pressurized Water Reactor, the water acts as a coolant of the core by removing heat. The high temperature and pressure of the water drives a steam generator that in turn runs an electric power generator. In the Boiling Water Reactor, the water pressure is low and it comes to boil at approximately 285°C in the core.

- Small Modular Reactor Technologies

  Small Modular Reactors can be prefabricated in advance in construction facilities and then can be transported to sites of interest where they can be readily installed upon arrival in a "plug and play" manner. This reduces capital costs and assembly times.

These reactors a great for small grids (due to their small size) when no large reactors can be supported. It enables Utilities to scale production according to demand needs.

- Advanced Gas-cooled Reactor (AGR)

These reactors use carbon dioxide as coolant (i.e. gas-cooled) and graphite as moderator. The fuel is enriched uranium oxide in pellet form. The carbon dioxide can reach high temperatures such as 650°C when it passes through the core, to finally reach the steam generator. It achieves a high efficiency rate of 41% due to the high temperature [64].

- Versatile Test Reactor

In 2019, the building of a Versatile Test Reactor has been announced. It a new technology of nuclear reactor that promises very high neutron energy fluxes as compared to current available fluxes. That will be the case because of the capability of performing irradiation testing at higher energy fluxes [66].

- Traveling Wave Reactor (TWR)

The Traveling Wave Reactor technology places a small nuclear core (e.g. enriched uranium) within a large amount of non-fissile material (e.g. depleted uranium). In the core, neutrons are responsible for transforming ^{238}U into ^{239}Pu; this is called breeding. When the breeding continues until enough fuel is produced, then the fission becomes self-sustained and the core is ultimately burnt out. Over a long period of up to 6 decades, the fission reaction gradually moves from the center to the outer layers, hence the name Traveling Wave Reactor. The main advantage of this nuclear technology is the high fuel utilization that requires no reprocessing and diminishes the need for enriched uranium [67].

Chapter 3 Electrical Power Systems

3.1 Introduction to Transmission System & Distribution Grid

An Electrical Power System (aka Electric Energy System) is defined as a network of interconnected electrical components which are used to generate (supply), transmit and consume use electric power. These electrical components may comprise of generators, transmission and distribution lines, transformers, buses, circuit breakers, loads etc.

The electric grid that supplies power to homes and industries in a geographically extended region is the most apparent example of such a system. The electric grid can be divided in three complex interconnected domains: the generation domain, the transmission system, and the distribution grid.

The generation traditionally includes bulk generation power plants which are delivering electrical energy to end users via electric networks known as transmission and distribution.

3.1.1 Generation

Traditional, when we refer to electric power generation we mean bulk generation, that is centralized power generation of high capacity by a few large plants that are remotely situated with respect to the cities and industries that electricity is transferred to.

Bulk generation refers to electricity production from renewable as well as traditional non-renewable resources. These sources are of various types, namely variable renewables, such as wind and solar; non-variable renewables, such as hydropower, geothermal, hydro pump storage, biogas and biomass; or traditional base load sources such as nuclear, coal, natural gas and petroleum. Bulk generation also refers to large scale centralized energy production systems directly connected to the transmission grid. Due to long distances that electricity has to be transported before reaching the consumers, a significant portion of energy is lost.

An alternative to bulk generation, is the decentralized generation which comprises of many small scale energy resources (aka DER, i.e. Distributed Energy Resources) usually connected directly to the distribution grid. Distributed energy resources (distributed generation) are located near to consumption. This way the electricity losses are minimal and the infrastructure is less costly. In the future, a source of potential DER may be the electrical vehicles. Smart Grid technologies will enable the expansion of variable renewables because the availability of real time information will allow utilities to manage power supply, consumption and power quality.

3.1.2 Transmission

The transmission is the electrical system that transmits electricity power in large amounts from generation sources to the distribution grid via high voltage to medium voltage substations. The transmission system is operated by Transmission System Operators, known as TSOs. The responsibility of a TSO is to keep stability on the grid by maintaing a balance between power supply and demand throughout the transmission system [Figure 3.1].

In modern electric grids, the generation and transmission systems are operating at high voltages incorporating automation and control equipment. Centralized SCADA and EMS systems are installed to interact with electrical equipment through Remote Terminal Units (RTUs).

Figure 3.1 Power Lines of high voltage, like these, transmit electricity over long distances

3.1.3 Distribution

7.5 Where the transmission system ends, the distribution grid begins. The limit is the high to medium voltage substations. DER assets and industrial, commercial and domestic users are connected through metering points to the distribution grid. DER assets include not only distributed generation units but also distributed storage systems. The distribution grid is managed by Distributed System Operators (DSOs). The responsibility of a DSO is the efficient operation, the development and the maintainance of the grid.

The Distribution Grid involves the final stage of the electrical grid which distributes electricity from the substations (on the boundary with the Transmission System) to residential areas, industry, and other end users. In order for the power to be delivered properly according to the end user's needs, the electricity is directly fed to medium voltage users (e.g. industrial consumers) or further stepped down to low voltage (e.g. 230V/400V) through step-down transformers for domestic and commercial use. There are two voltage levels in the Distribution Grid, namely the medium voltage (e.g. 20kV) and the low voltage (e.g. 230V/400V). The distribution grid consists of distribution overhead lines and underground cables, wooden and concrete poles, step-down transformers, switching gear and protection circuits that deliver electrical power safely.

Historically, the Transmission System and the Distribution Grid were operated by the same utility company. In the 1990s and the 2000s, many countries and the EU member states have liberalized the electricity market so as to cause the separation of the electricity generation, transmission, distribution sectors.

3.2 Smart Grid

The concept of the electrical Smart Grid (SG) emerged in the early 2000s and the interest to the gradual and successful transition from the conventional to the smart grid (SG) culminated in the 2010s.

In recent years, the great interest of various stakeholders (i.e. scientific community, national governments, industry, companies, organizations, independent bodies and regulatory authorities, citizen groups etc.) to achieve specific strategic goals, resulted in many scientific studies and practical attempts to introduce various SG technologies and concepts in the current electrical power systems. SG technologies are indispensable to the clean energy development.

Smart Grid aspires to become the energy efficient electrical system of the near future that is sustainable and depends on renewable energy resources. In other words, a sustainable power system that achieves safety and supply security along with limited energy losses.

Many on-going projects are being deployed worldwide in developed and developing countries.

The Smart grid is essentially the evolution of the current electrical systems where energy is combined with control and communication infrastructure to achieve enhanced flexibility, resilience, economy, and high shares of renewable energy sources.

3.2.1 What is a Smart Grid?

There is no common definition of what a Smart Grid (SG) is. It usually depends on the main aspects that are focused and the institution or body that provides the definition. The key features of Smart Grid are efficiency, reliability and flexibility. Also, the centralized generation is combined with distributed generation in an automated power grid [68].

Following are two definitions of the SG concept:

- A Smart Grid is an electrical system that integrates the behavior of all users connected to it in a smart manner. As users are considered the producers, the consumers and the prosumers (producers and consumers at the same time). The result is the supply of quality, efficient, sustainable, economic and secure electrical services.
- Smart Grid is an electrical grid that incorporates automation control, communication systems and information technology systems. These systems can effectively achieve power flow monitoring all the from energy production units to consumers. Power flow control and load curtailment can take place when necessary for balancing supply and demand in real time.

The term “Smart Grid” is generally used to refer to a broad spectrum of systems, technologies, infrastructures and concepts. For example, Renewable Energy Sources (RES), Energy Storage, Electric Vehicles (EV), Advanced Inverters, Smart Meters, bidirectional flow of energy and data (ICT infrastructure), Advanced Metering Infrastructure (AMI), SCADA systems, synchro-phasor devices, Microgrids, Demand-Side Management and Demand Response (DSM/DR), self-healing, Internet of Things (IoT), liberalization of energy market etc.

Within the Smart Grid concept, the Renewable Energy Sources can be utilized not only as bulk-generation plants (along with the traditional utility-scale sources) but also as sources of

Distributed Generation (DG) which are generally known as Distributed Energy Resources (DER).

The notion of Smart Grid embraces the power generation segmant, the electricity transmission system, the distribution grid, the metering and billing processes, other end-user services and the energy market. In essence, the SG concept spans all along the electricity value chain.

Figure 3.2 shows graphically the traditional grid and the emerging Smart Grid which includes the ever increasing shares of Distributed Energy Resources (DERs) and the emergence of prosumers (producer–consumer).

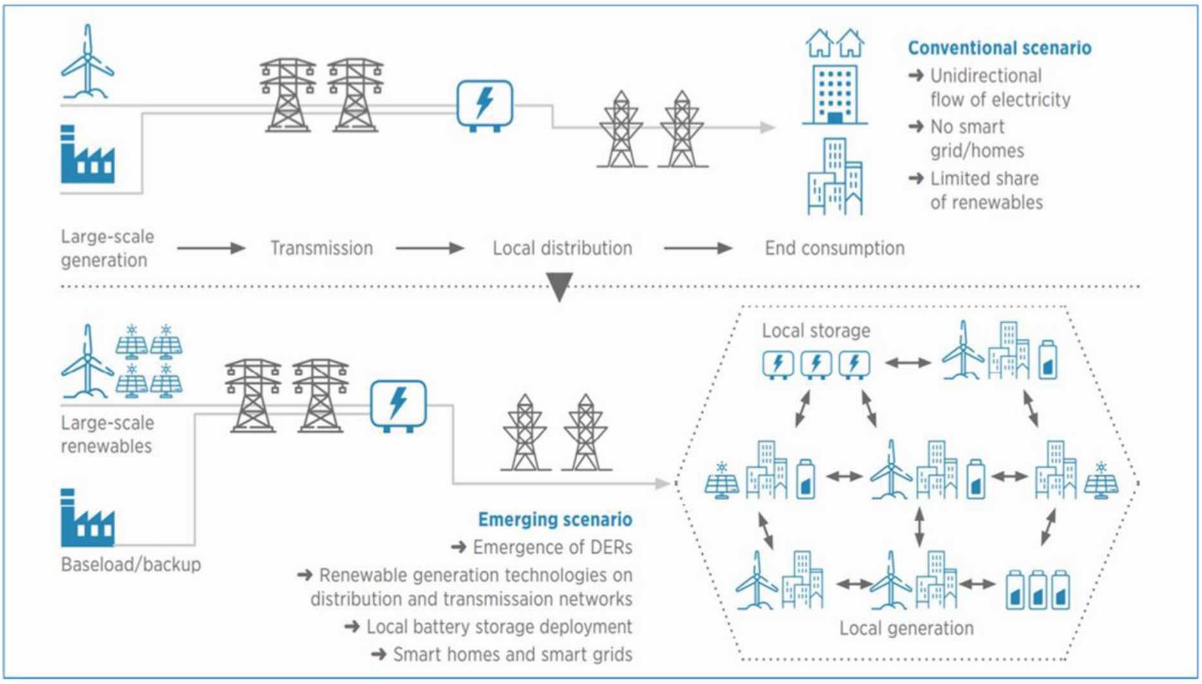


Figure 3.2 Traditional Grid vs Smart Grid

Some of the segments (e.g. generation, transmission and distribution) were in place before the smart grid concept. Nevertheless, all of them are affected in a new way by means of innovative SG technologies in order to address today's energy and climate challenges effectively. For example, the traditional electrical grid cannot cope successfully with the challenge of high RES penetration, thus failing to address the air pollution and climate change resiliently and reliably; unless new emerging SG technologies are implemented.

3.2.2 Objective & Benefits of Smart Grid

The basic objectives of Smart Grids are:

- Energy Efficiency
- Environmental Benefits
- Supply of high quality Services

Utilities, regulators, customers as well as the environment can reap the benefits of the Smart Grid deployment. The benefits of implementing SG solutions include:

- Integration of Renewables and electricity accessibility
- Power purchase cost reduction
- Improved customer satisfaction and financially healthy utilities
- Reduction of Transmission and Distribution losses
- Efficient asset management
- Self-healing capabilities and enhanced grid visibility
- End-user options such as time-of-use tariffs, DR programs, net energy metering etc.
- Improved QoS, reliability and peak-load management
- Reduced Greenhouse House Gases (GHG) emissions, etc.

3.3 Transition from Traditional Grid to Smart Grid

There is a distinct difference between the conventional grid and the Smart Grid. The traditional electrical grid is a one-way energy transmission system. But in the last decade conventional grids are undergoing a significant modernization. SCADA systems, integration of RES, microcontroller-based relays among other have already been implemented.

Conventional and Smart Grid differences are presented in the following Table 3.1, based on the grid characteristics.

In the past, the electrical network infrastructure was designed and implemented taking into account the fact that electricity was to be delivered from many large-scale centralized power systems based on fossil fuels to very many domestic, commercial and industrial consumers. The electricity is delivered via a transmission system and a distribution grid power flow in one direction, that is, from production to consumption. The nuclear and hydro power stations are following the variability of demand and can adjust the electricity production to follow the load [69]. This way, the electric grid equilibrium is always maintained.

Table 3.1 Comparison between conventional and smart grid [68]

Characteristics	Conventional Grid	Smart Grid
Communication method	Unidirectional, not real-time	Bidirectional, real-time
Technological base	analog / electromechanical	Digital
Power flow control	Limited	Pervasive
Power supply method	Centralized power generation	Centralized & decentralized power generation
Self-heals	Prevention of further damage	Automatic detection & response to actual and emerging transmission and distribution problems
Operation & Management	Artificial device calibration	Remote monitoring
System topology	Radial structure	Network structure
Control system	Regional	Pan-regional
Consumer motivation and engagement	Consumers are uniformed and do not participate in the power system	Consumers are informed, involved and active
Power quality for modern needs	Focused on outages rather than power quality problems	Quality of power needs industry standards and consumer needs
Generation	Relatively small number of large generation plants	Very large numbers of diverse distributed generation and storage devices deployed to complement large plants
Markets	Limited wholesale markets, still to find the best operating models	Mature wholesale market operation in place
Asset optimization & efficient operation	Minimal integration of limited operational data with Asset Management processes/technologies	Expanded sensing and grid conditions measurement. Grid technologies deeply integrated with asset management processes to most effectively manage assets and costs
Emergency recovery	Manual recovery	Self-healing & auto recovery
Price information	Limited	Access to price information
Customer choice	Limited choice of optional function	Wide range of optional function

In case of imbalances, the grid operators have at their disposal specific control mechanisms to steer the grid to balance. For example, whenever generation fails to meet the load, then the spinning reserve is used to balance the demand. Although spinning reserve is quite effective, it also bares certain disadvantages. Spinning reserve is costly and carbon intensive as a stability maintaining method (i.e. supply and demand balance), since it requires the generation stations to be running constantly and thus consume fuel in order to be always ready to be brought live fast whenever necessary.

On the contrary, the use of RES in the electrical grid provides clean energy, but it causes operational problems in terms of managing the conventional generators to respond to temporary variations between renewable power supply and consumer load. The power grid operators are confronted with two possible ways to manage the imbalances: either to further expand the traditional spinning reserve operation thus inducing higher costs [11], or to realize innovative technics to effectively tackle the imbalances [12, 69].

3.3.1 Conventional and Smart Grid Comparison

The smart grid (SG) is the new paradigm that intends to transform the conventional grid, introducing the protection of natural ecosystems through renewables as well as a spectrum of advantages spanning from enhanced reliability and high service quality to the efficient use of grid infrastructure. The transition from the conventional to the smart grid is illustrated in Figure 3.3.

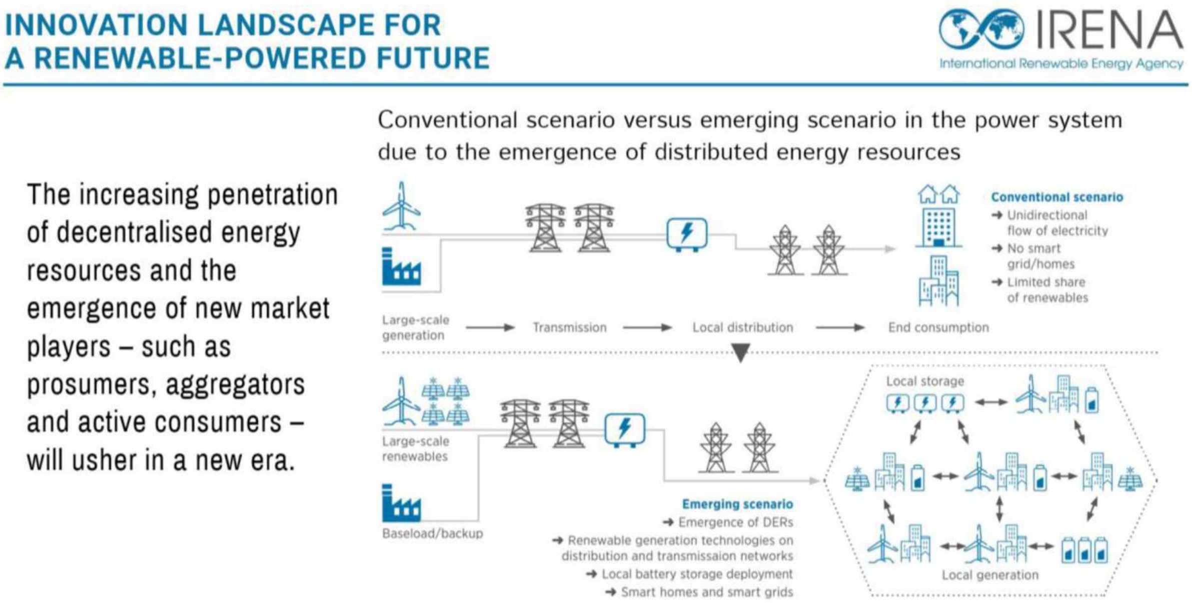


Figure 3.3 Transition from traditional to Smart Grid (source: IRENA)

Although the SG comes with many environmental and economic benefits, important security and privacy issues challenge the whole effort for grid transformation. The reason is that many different technologies, old and new ones, have to be combined in a seamless and compatible way [1]. To mention but a few, the SG technologies include: SCADA control centers, microgrids, AMI, electric vehicles, synchrophasor systems etc. [14], [59].

The gradual transition to Smart Grid, which is already undergoing in most developed countries worldwide, requires the modernazation of the current grid assets. For example, by installing scensors, IED, RTU, PLC, MTU etc and connecting them to SCADA Control Centers to use the acquired data for motoring and management purposes.

Chapter 4 Integration of RES into the Grid

4.1 Distributed Generation and Integration of Renewable Energy Resources

Many countries, including Greece, have set ambitious targets for decarbonization and high RES penetration. That is the case for both on-grid centralized (aka 'bulk') and on-grid distributed generation. A significant step forward has already been taken in the last decade around the world since many on-land and off-shore wind farms are already connected primarily to the transmission system and also many rooftop solar and on-ground solar PV systems have been installed mainly to the distribution grid. Moreover, many VRE projects are currently ongoing (in the implementation phase) and many are still to come worldwide (in the design phase), continuing to increase the penetration of VRE (variable renewable energy) systems in the energy mix of electricity generation.

The high penetration of VRE systems – primarily wind and solar PV – to the Electric Power Systems (transmission and distribution grids) is a great step towards sustainability and decarbonization of the energy sector. But along with their integration come various challenges for the grid and the most important is the power quality.

4.1.1Penetration

Penetration is the amount of electrical energy generated by a particular energy source (e.g. wind or solar energy generating systems) as a percentage of the total amount of energy. In the case of renewable resources (e.g. mainly solar and wind but also hydro, geothermal and biomass), the renewables penetration is the percentage of the total electricity power generated (or the amount consumed) in a given power grid.

Penetration of RESs in the grid can be defined as the percentage of the total output of all RES power generating systems with respect to the total load power, as shown in the following equation (1):

$$RES_{penetration} = \frac{\sum_{t=1}^{T}\sum_{i=1}^{N_{RES}} P_{i,t}^{RES}}{\sum_{t=1}^{T}\sum_{i=1}^{N_{load}} P_{i,t}^{load}} \times 100\% \tag{1}$$

where $RES_{penetration}$ represents the penetration percentage of RES, $P_{i,t}^{RES}$ is the output power of the *i*th RES electricity generator at time t, $P_{i,t}^{load}$ is the demand power of the *i*th load node at time t, N_{RES} and N_{load} represent the number of RES electricity generator and load nodes respectively, and T is the total operating time [70].

There are calls for generating not just up to 100% of electricity generation through renewable energy sources, but far more, up to 200% or even 300% so as to meet the needs for over-production, heating, cooling and transportation [71].

RES over-production (aka "over-generation" or "over-supply") can also be deemed as a security against RES variability and intermittency, as well as an opportunity for increasing storage capacity when RES power generation is abundant.

It is important to note that there are alternative definitions in the scientific bibliography in terms of the share of RESs in power systems and the appropriate choice depends on the emphasis we need to place on various aspects.

The percentage of RES in the electricity generation mix is usually measured by:

- the renewables' percentage in the electricity generation: the portion of renewables electricity production to the total electricity production on an annual basis,
- the renewables' percentage of the total power capacity: the portion of the connected renewables' power to the total power capacity,
- the instantaneous percentage of renewables with respect to the load: the portion of total power production of renewables to the total consumption capacity at any moment in time [72].

According to the "Renewable Energy Capacity Statistics 2022" of IRENA, the renewable energy share of electricity capacity in 2021 of some selected countries (and groups) was as follows:

- Greece: 54.5%
- Europe: 52.1%
- EU (27): 79.6%
- Germany: 60.5%
- France: 42.7%
- Denmark: 63.9%
- Spain: 55.7%
- UK: 46.5%

- USA: 27.5%
- China: 42.9%
- World: 38.3%

It is important to note that the above percentages refer to installed power capacity and do not directly reflect the actual annual energy generation shares. Another key note is the fact that certain countries are dependent on energy imports such as Greece that imported the 18% of electric energy in 2020 to balance the demand.

4.2 Challenges due to High Penetration of RES

The penetration level of RESs, especially solar and wind, has significantly increased in the past decade and its growth rate is likely to remain high due to investment cost reductions and in order for the GHG emission targets to be achieved by 2050. Nevertheless, the high level of intermittent RES integration into the electrical power grid is followed by serious technical challenges.

The intermittency and randomness of the most common and widespread RESs, i.e. wind and solar, increase the unpredictability and variability of the electricity supply. Other RESs such as biomass, biogas and geothermal are non-intermittent and are more predictable. Still their power capacity (and therefore their penetration level) is relatively low. In general, reservoir hydroelectric is neither variable nor low capacity but hydro capacity alone cannot compensate for both wind and solar capacity (and penetration) levels, except for the very rare cases where water stream capacity is abundant (e.g. Norway).

In traditional systems, the electricity generation resources were dispatchable and the goal was to meet the variable and stochastic demand needs. However, in the case of VRESs also the supply side is not adequately predictable despite the use of forecasting methods. The precarious nature of VRESs causes uncertainty in balancing the load and keeping the stability of the power system by regulating the voltage and frequency levels [73].

Since the level of renewables penetration is expected to grow, a reassessment of the current energy balancing paradigm is absolutely necessary.

4.2.1 Frequency

The increased volatile feed-in power of VRE systems has resulted in grid frequency fluctuations. The grid remains stable when the frequency variations are minimized. Distributed generation units are playing an important role in diminishing the fluctuations. Grid codes and ancillary services that are incorporated in modern advanced inverters provide with very promising solutions to the frequency fluctuations. Sections 4.3.2 and 4.3.3 illustrate the proposed solutions in detail.

4.2.2 The Duck Curve

A well-known example of the challenges faced by power system operators (TSOs and DSOs), when there is a rapid expansion of solar energy systems, is the so called "duck curve" because of its resemblance to a duck [74]. It was first detected and identified as a potential problem in 2013 by the California Independent System Operator (CAISO; i.e. California's TSO), due to the large-scale deployment of solar power systems [75].

Figure 4.1 illustrates the "duck curve" effect of abundant solar PV power on a typical day in late March in California. Specifically, it shows the difference between power demand in the HV transmission system and the amount of the distributed solar PV power during a typical day in late March. During a sunny day, solar PV power supply can be abundant but towards the evening it quickly diminishes whereas the consumption electricity demand remains high and even reaches its peak.

The effect is most intense in the springtime because the weather is sunny and the temperature is cool to moderate; so the solar PV production is high. On the contrary, the consumption demand is generally low since air-conditioning or heating (through electricity) are not much in use [74].

The duck curve reflects the difference of electricity demand and the quantity of available solar PV power during the day, in other words it's the "Net Load" as appears from a Transmission System point of view. It resembles to a duck with a steep rising neck as shown by the purple line depicting the "Net Load" in the following graph in Figure 4.1.

The challenge for utilities is to keep the balance between production and load in the late afternoon by quickly ramping up energy production (other than solar). As can be seen in Figure 4.1, a total of 15GW of electrical power must come online in a matter of just 3 hours. The addition of extra solar PV power systems to the grid tends to stress the grid and its electrical components even more.

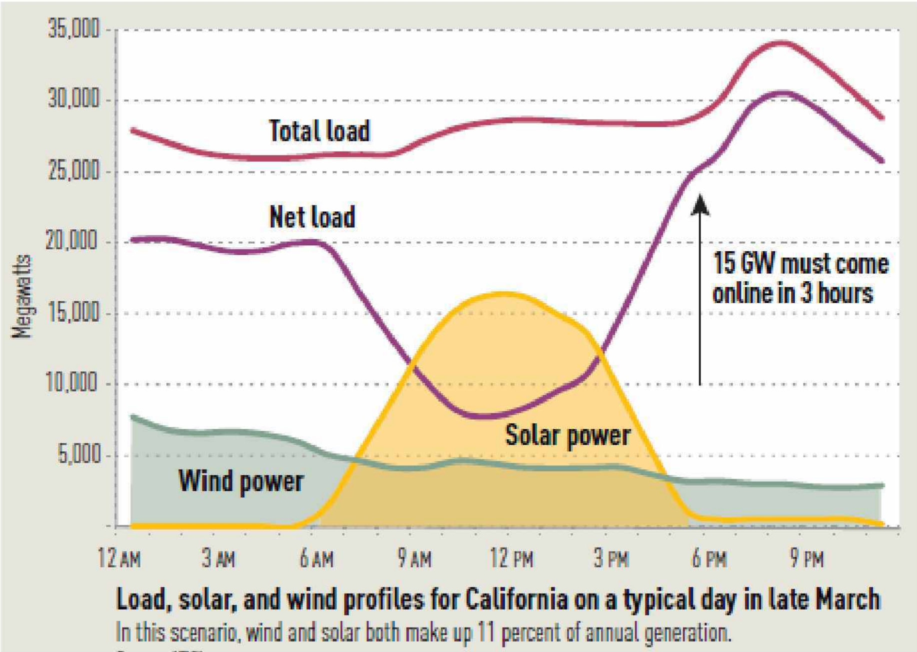


Figure 4.1 Shape of the Duck Curve (source: NREL)

The curve shows the influence of the growing distributed solar PV power production on the demand for bulk generation. As the solar PV power production increases, the bulk generation demand decreases during the day reaching its lowest point at about midday (when solar generation is high), forming the back of the duck. As the sun sets the solar PV production falls to zero and the power demand grows very fast, forming the neck of the duck. The more the share of solar PV power in the grid, the steepest the demand curve (net load) as shown in the Figure.

In the case of California ISO (i.e. California's TSO), the growth of PV power supply until 2020 was such that the duck neck was getting steeper than anticipated according IEA [76].

4.2.3 Over-generation and Curtailment

Another challenge of high wind and solar PV adoption is the possibility of generating more energy than consumed during certain periods, leading to over-generation. In case of not enough storage capacity or any other alternative, system operators are forced to curtail solar PV generation. Curtailment can be a useful tool and has little impact when it takes place only occasionally during the year, but it could have a great impact on the environmental and economic benefits of solar energy at high penetration levels. That is so because as the penetration level increases so does the rate of curtailment (although not proportionally). This makes system operators to use curtailment of PV power generation, and therefore preventing its economic and environmental benefits.

When curtailment is used occasionally, it can be beneficial. At high penetration levels, curtailment tends to be more frequent and further actions are needed to alleviate the issue.

4.2.4 Power System Transformation

Currently as well as during the last decade, electrical power systems around the world are confronted with tremendous changes. These changes are ongoing and are expected to be prevalent in the near future. The main reason behind this transformation are:

- the ever-decreasing installation cost of solar and wind energy systems,
- the widespread deployment of decentralized energy resources (DER), for example rooftop solar installations and electric vehicles (EVs).

This transformation requires a different way on how power systems are planned and operated. This means than policy makers, power system planners and all relevant stakeholders must proactively navigate towards the common goal of power system transformation (PST) [77].

An important objective of PST is the enhancement of power system flexibility. Due to the increasing levels of VRESs, potential operational issues and high-impact events jeopardize the stability, the security and the constant availability of power supply. Flexibility is universally considered as the “antidote” to these hazards and therefore power system flexibility has become a major priority. Lack of flexibility results in resilience degradation and leads to green electricity losses via widespread VRES curtailments [77] which are undesirable and uneconomical.

Since generation and consumption must be always balanced, flexibility is also necessary to manage variability and uncertainty through all timescales, ranging from short-term (seconds – hours) to medium-term (hours – days), as well as to long-term (days – years).

In the past, the main concern with regard to flexibility was the ability to effectively deal with the variable electricity demand, the loss of energy production plants and/or a transmission power line. In modern systems however, apart from managing outages is also important to address the variable electricity supply as VRES levels of penetration increase.

Table 4.1 shows the issues addressed by flexibility in terms of timescale. System flexibility can deal with various problems that range through all timescales (from milliseconds to years) [78].

Table 4.1 Timescales of power system flexibility issues [78]

	Short-term flexibility			Medium-term flexibility	Long-term flexibility	
Timescale	Subseconds to seconds	Seconds to minutes	Minutes to hours	Hours to days	Days to months	Months to years
Issue	Address system stability, i.e. withstanding large disturbances such as losing a large power plant.	Address fluctuations in the balance of demand and supply, such as random fluctuations in power demand.	Manage ramps in the balance of supply and demand, e.g. increasing electricity demand following sunrise or rising net load at sunset.	Decide how many thermal plants should remain connected to and running on the system.	Manage scheduled maintenance of power plants and larger periods of surplus or deficit of energy, e.g. hydropower availability during wet/dry season.	Balance seasonal and inter-annual availability of variable generation (often influenced by weather) and electricity demand.

In order to tackle the aforementioned technical challenges, it is imperative to increase the flexibility of the power systems. Consequently, flexibility is a crucial factor in the evolution of the power systems and an integral concept of the Smart Grid (SG).

The high penetration of VRESs is the catalyst for the fast transformation towards the SG of the of future, and the consequential increase of operational complexities [73].

4.2.5 Flexibility

Power system flexibility is a main feature of the power system transformation (PST).

The concept of power system flexibility is influenced by the evolution of technology and power markets. In 2008, the IEA defined the flexibility as “the ability to operate reliably with significant shares of variable renewable electricity”. In 2011, the definition was precisely defined: “Flexibility expresses the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise” [77].

The resilience of power systems can be compromised when there is not enough power system flexibility, leading to losses of substantial amounts of green electricity due to excessive curtailment of VRESs [79].

As mentioned previously, the issues arising by the ever increasing share of VRE sources is the driving force of PST. Higher levels of VRE penetration require higher levels of power system flexibility too. The IEA has proposed a specific phase classification that reflects VRE impact in relation to the penetration levels.

VRE integration phases

The ever increasing VRE penetration, specifically due to wind and solar PV, leads to challenges for the power system. The importance and magnitude of these challenges have been divided into six phases by the IEA.

As shown in Figure 4.2, there is a framework of six different phases that can be used as a guide to the measures needed to support system flexibility. Key transition challenges are identified in each phase that have to be tackled for going to the next level of renewables integration. A specific group of problems appear as penetration of renewables increases. Flexibility options are also defined to enable transition from one phase to the next higher one [80].

In Figure 4.3, the annual VRE shares are presented along with the corresponding integration phases for certain regions and countries. As of 2018, Phase 4 is the top integration level currently reached by Denmark, Ireland and South Australia. Many others are still in phases 1 and 2, having 5% to 10% levels of penetration [78].

The general direction of the transition is common for most countries. The increase of VRE shares are affecting more and more the power system operators (TSOs and DSOs) around the world. Higher levels of renewables integration are expected and therefore the requisite efforts to improve the flexibility [78] as presented in Figure 4.2.

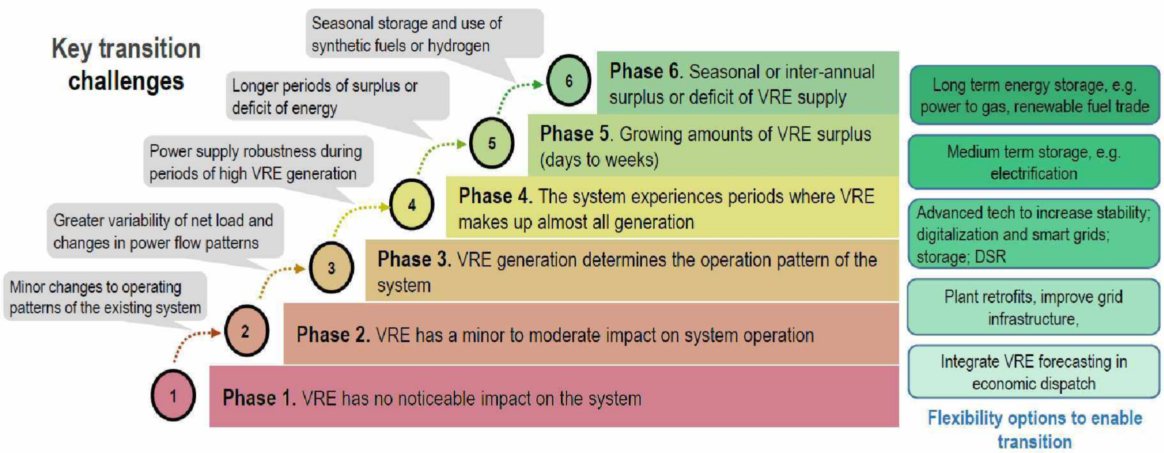


Figure 4.2 Phases of renewables penetration [80]

It's worth noting that there is no exact one-to-one mapping between VRE integration phases and VRE penetration levels as can be seen in Figure 4.3. For example, Australia and Uruguay are in lower VRE integration phases compared with Kyushu and Ireland respectively, but their VRE penetration percentages are higher. The specific characteristics of each power system (e.g. limited connectivity to other regional power systems) and the way the VRE systems are distributed within the grid, are key factors that determine the exact VRE integration phase with respect to the VRE share.

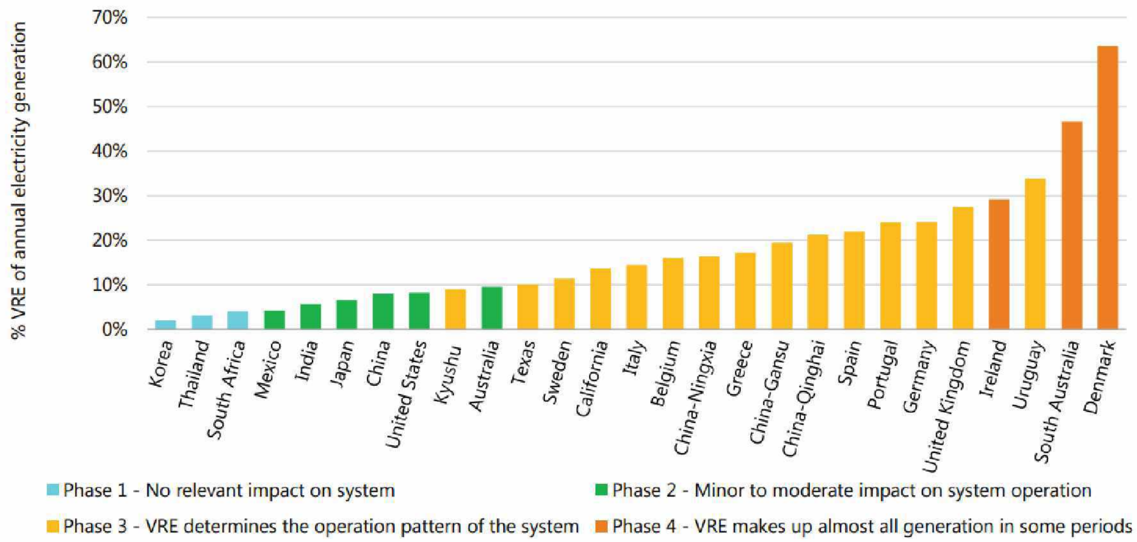


Figure 4.3 Annual share of renewables and integration phases in 2018 [78]

An operational Smart Grid is supposed to alleviate the problems and challenges that are caused by high shares of renewables. So, the point is how to achieve electrical power system that effectively incorporate technologies and methods and what its specific characteristics ought to be.

Several proposed solutions are discussed in the following section 4.3. The proposed solutions are intended to be used in combination since there is no single "cure-all" solution. Each one is appropriate for addressing a specific problem or a limited range of issues arising by high VRE shares. These solutions include SG technologies, flexibility methods as well as regulations and grid codes. All of them together will lead to the desired result of sustainable, flexible and reliable electrical grid. In other words, it is the appropriate combination of the above technologies and methods that will result in a total beneficial solution for the grid, the society and the environment.

4.3 Proposed Solutions

A Smart Grid (SG) entails technology applications that will enable (among others) the integration and the higher penetration of renewable energy sources (RESs). SG technologies can be deemed as enablers and catalysts of the so-called Power System Transformation (PST). In that context, there is a host of proposed technological solutions available to comprehensively address the challenges presented previously in §4.2.

Smart Grid (SG) takes advantage (over conventional grids) of modern information and communication technology (ICT). Conventional power systems cannot effectively predict the intermittent RES energy supply and cannot control the energy demand variability. Besides, effects on the grid depend on different levels of penetration of variable renewables as well as other factors such as generator type (e.g. wind or solar) and grid characteristics [105]. Thus, reliability is a major concern. In such cases, control systems, energy storage systems (ESS's), curtailment strategies, demand response and other smart grid technologies are proposed to ensure flexibility and reliability to the grid.

4.3.1 Interconnection and Transmission infrastructure

Transmission (intra-regional) and interconnection (inter-regional) infrastructures play a key role for various issues such as the security of supply, the efficiency and the integration of high shares of renewable energy sources.

Grid expansion and upgrade

Electricity network reinforcements and the shared use of hardware resources across neighboring regions can substantially improve power system flexibility. Interconnections permit an load increase to be fulfilled by excess generation in a another adjacent transmission system when local generators operate at maximum output [81]. Interconnections are very significant when it comes to flexibility of systems which integrate high levels of VRE sources. Additionally, the reinforcement of transmission infrastructure can also enable the share of storage facilities that store energy surplus from generation plants situated very far away.

In conclusion, grid expansions and upgrades can facilitate the full use of currently under-utilized flexibility resources due to bottlenecks [81].

Policy makers should play their influential role in encouraging grid interconnectivity between regions which enable further system flexibility as described above.

It is well known and very common that electricity is generated far from where it is consumed, and this is the case not only for conventional generation plants but also for VRE systems (usually wind farms and solar parks). Since 2010, the growth of VRES capacity has been remarkable in many parts of the world, but it was not followed by an equivalent grid expansion investment. So, the transmission lines lack the capacity needed to allow for all the renewable energy supply to be transferred from parts of the grid where it is in excess to other parts of the grid where it is needed.

A great example is that of Texas, where energy curtailment dropped from 17% to 0.5% (from 2009 to 2014 respectively) mainly due to additional transmission lines which were constructed during that period. The new transmission lines are effectively transferring the wind energy from grid congested regions to where it can be used [82].

Grid Congestions

A grid congestion (bottleneck) occurs when the electrical power fed into a part of the grid is more than the amount of power that is taken off. In order for the grid to remain stable, these two amounts have to match in all instances. When this balance is disrupted in favor of the feed-in power, then a congestion starts in that part of the grid and the electrical components get under stress approaching their limits. A congestion is an overload that takes place in a part of the grid which can be detrimental to its components and can result in power outages and widespread blackouts. To prevent from any serious problems to emerge, system operators intervene by curtailing surplus power production so that a secure and stable supply of electricity is guaranteed.

Bottlenecks occur not only in the transmission but also in the distribution grid, and they can be caused by both conventional power plants and renewables.

Total Grid Expansion is Inefficient

Grid expansion is a long term solution to prevent bottlenecks, but not entirely to exclude them. In economic terms, it would be inefficient and expensive for any national or regional grid to be entirely upgraded to the point that the maximum amount of electrical power can be transmitted and distributed without any bottleneck occurrences under any circumstances.

The reason is that the worst-case scenario power peak events happen very rarely, for instance only a couple of times per year and only for a few hours. Thus, it will always be necessary for the system operators to curtail surplus power but much less frequently and at a lower cost since only the absolutely necessary curtailment reimbursements will be paid to producers. In a nutshell, most bottlenecks should be prevented in the future but not all.

4.3.2 Ancillary Services

Ancillary Services (AS) provide the necessary functions for ensuring reliable power system operation. Grid operators (primarily TSOs and secondarily DSOs) have the obligation to use ancillary services to guarantee reliable power supply. That means that frequency, voltage and demand must constantly be monitored and controlled to remain within certain limits. These continuous corrections in the grid characteristics are the ancillary services. The most popular such service is the balancing energy, also known as frequency control.

Ancillary Services include four distinct groups, as illustrated in the following Figure 4.4.

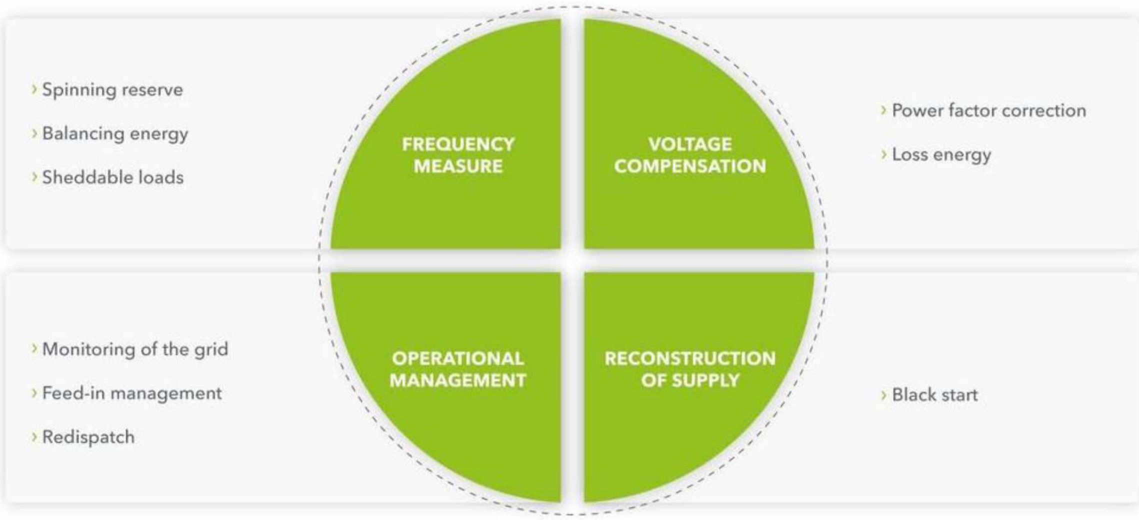


Figure 4.4 Ancillary Services are divided in four sections [103]

Ancillary Services are a spectrum of operational functions which the TSOs use in order to guarantee the system security.

The **Ancillary Services** include the followin functions:

- Balancing Energy or Frequency Control/Response; it maintains the system frequency with very fast response,
- Loss Compensation; compensation for losses due to transmission of energy,
- Black Start; the capability to start a grid after black-out,

- Fast Reserve; it provides additional energy when necessary,
- Voltage or Reactive Power Control, etc [83].

Balancing Services

Balancing Service is a short-term method to diminish frequency fluctuations in the power system. **Balancing Services**, also known as “**control reserve**” or “**frequency control**”, is an ancillary service that guaranties and secures the power supply [75]. Balancing Services include Balancing Energy and Balancing Capacity.

Balancing Energy is the energy that is used by transmission operators to perform the maintenance of grid frequency within certain narrow limits around the nominal value (e.g. 50Hz in Europe). **Balancing Capacity** is the flexible capacity that a balancing service provider is obliged to keep available for a certain period in order to provide a part or all of it as balancing energy [75]. Figure 4.5 illustrates the balancing services according to ENTSO-E (European Network of Transmission System Operators for Electricity).

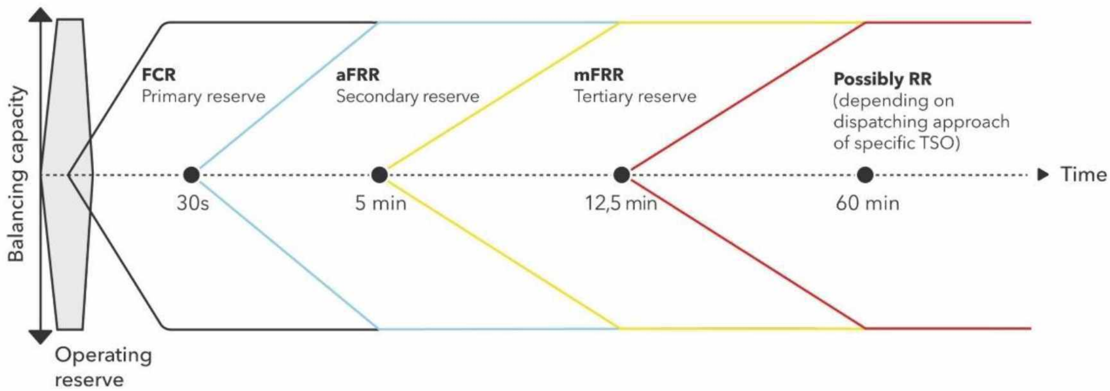


Figure 4.5 Balancing Services according to the system envisioned by ENTSO-E [75]

The growth of VRE generation and the subsequent increase in penetration levels and the liberalization of the electricity markets, have brought focus on the efficient use of generation and transmission facilities. As a result, the transmission infrastructure operates close to its limits and the Ancillary Services have to play their significant role here.

The challenge

The increasing share of VRE resources connected to the grid have changed the dynamics which rely on traditional synchronous generators. Interconnections and energy markets have resulted in further reducing the fossil fuel power generation sources.

It has been suggested [83] that emerging VSC-based HVDC systems have significant potential in supplying ancillary services such as robust fast controls in a similar or even better way than the conventional AC systems in the context of interconnected and offshore grids.

The liberalization of the electricity markets gives the TSOs access to an array of services from a broad range of AS providers, such as generators but also consumers through Demand Response (e.g. customers that change their consumption patterns as a service to aid the balancing of the power system). The TSOs can have various flexible options at the disposal to make efficient operational decisions [84].

Inertia and increasing VRE penetration

The term “inertia” is commonly used in relation with power generation and transmission systems to refer to the rotational energy that is stored in generators and motors that makes them tend to keep rotating. In essence, inertia inherently resists changes in frequency. This tendency to keep their rotation due to the stored energy, is very valuable in case of contingencies (e.g. power plant failures) since it can temporarily compensate for the lost power. The temporary response is practically available only for a short while (few seconds) but still enough for mechanical systems to detect the failure and respond appropriately.

Traditionally, inertia was provided by fossil, nuclear and hydro plants in ample quantities. Because of that, inertia was commonplace in planning and operation of power systems.

However, as the grid integrates ever more DER and VRE resources which use no rotating generators (and at the same time traditional power plants are decommissioned), the total available inertia in the grid decreases. Wind, solar PV and battery storage are all inverter-based sources which inherently lack inertia.

This fact raises the question about the need of inertia, the consequences of its reduction, its future role and how to maintain system reliability [85].

The conventional power plants inherently provide inertia because they turn the rotational energy of a generator to AC electricity through synchronous turbines. On the contrary, solar PV and battery storage systems produce inherently DC electricity which is converted to AC via a converter (in this case, an “inverter”) before fed into the grid. Wind turbines initially produce AC electricity, but inverters are more commonly used for efficiency reasons. So, all these DERs (wind, solar PV and batteries) can be referred to as inverter-based resources (IBRs). When IBRs are used instead of synchronous generators, then the total amount of inertia decreases in the grid [85].

Beyond Inertia: Grid-following & Grid-formin Inverters

Microgrids are zero-inertia systems that have been in operation for long. This shows that inertia is not always necessary for AC power systems normal operation [85, 86]. Actually, it is the traditional use of AC synchronous generators that has resulted in the notion of need for inertia and its reliance.

In Figure 4.6, a group of power systems (of selected countries/islands) with high shares VRE sources that are operational for many years without any significant problems.

Since the shares of VRE resources are expected to grow more, possibly aiming to 100% penetration in the future, it is obvious that inertia will keep diminishing to almost zero value ultimately. Even in scenarios of high but not 100% penetration, there will be periods even short ones that the system may operate with 100% IBR penetration like a microgrid. In such events the inertia will be negligible.

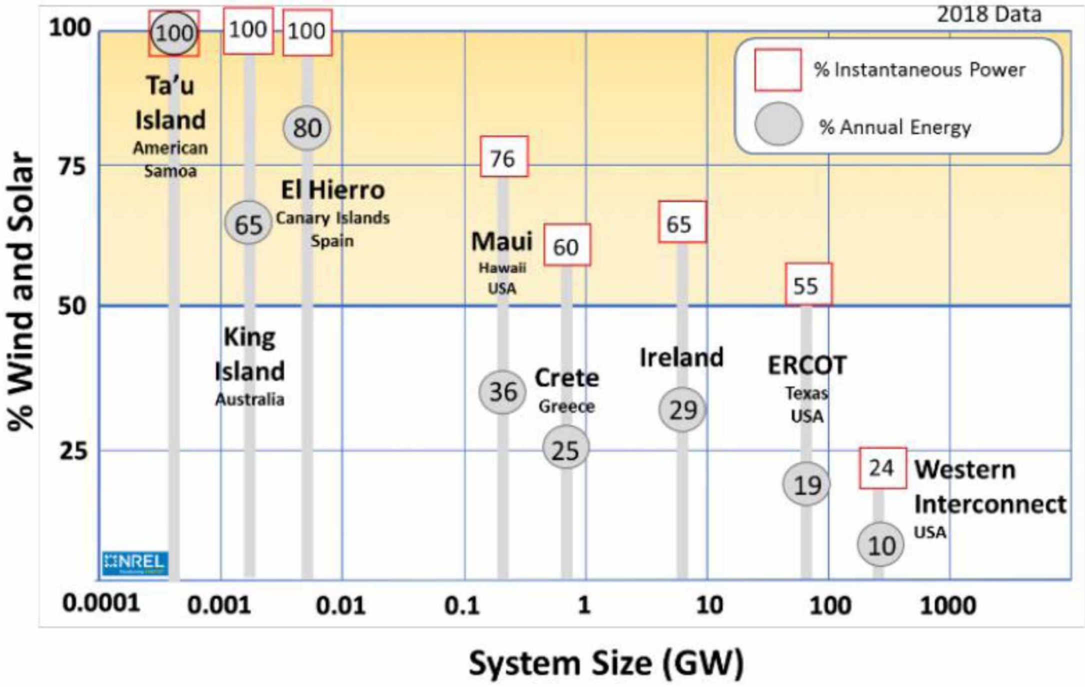


Figure 4.6 Annual and instantaneous IBR generation on selected power systems [86]

This situation brought to the forefront the requirement for more research and new techniques to maintain grid stability in general and frequency in particular. The results of the respective research were rather unexpected in terms of the traditional ideas that considered significant amounts of inertia as a prerequisite for power grid reliable operation.

Currently, the inverters of IBRs are monitoring the voltage and the frequency, and they inject electrical energy into the grid, self-synchronizing to the existing reference waveform of the synchronous generators. Such inverters are called grid-following due to the fact that they follow the already existing waveform in the grid.

When there are no grid-forming (i.e. creating a reference AC waveform) synchronous generators left in the grid, then the inverters shall be responsible to establish and maintain a reference AC waveform (voltage and frequency within certain limits) as happens in microgrids. So, the inverters should take up the responsibility to be grid-forming. Since grid-forming inverters make a wave form of specific voltage and frequency values, then they provide a synchronous AC system without synchronous generators [87].Nevertheless, even approaching 100% renewables does not necessarily mean 100% inverter-based resources or zero-inertia grid.

Apart from solar PV and most wind generation, many RESs deliver their power via synchronous generators such as hydroelectric, solar thermal, biomass, biogas and geothermal. Additionally, energy storage facilities, based on pumped storage hydro (PSH) technology, use synchronous machine and currently account for the largest energy storage resource in the world [87].

At present, the grid-forming inverters are advancing fast [86] and the need for zero or near zero-inertia grids must be further investigated and analyzed [85].

Conclusions and Research Needs

During the last century, almost all power generation was provided by synchronous rotating generators. The inertia in the form of stored kinetic energy provided the grid with enough time to react to sudden and unpredicted frequency declines due to faults, outages and other imbalances. The reason is that the traditional mechanical devices require a couple of seconds to react to frequency disturbances.

The replacement of conventional generators with IBRs (wind, solar PV and batteries) has two distinct effects which fortunately have counterbalancing effects. The first effect is the decline of the available inertia. But the second effect is the faster response of IBRs to sudden frequency changes as compared with conventional resources. Thus, they are the cause of inertia reduction but actually they don't need it as they address it by faster response times.

This situation represents a paradigm shift in the way we consider inertia and deal with frequency response. Inertia was considered to be the only resource that maintains system reliability but this has been demonstrated not to be entirely true.

As a result, the combination of inertia and mechanical frequency response required for maintaining system reliability, can be partly replaced to a considerable extent by the power electronics frequency response of IBRs and also the fast response loads, for example industrial loads, heat pumps and storage devices. These solutions show that reduced inertia is not inherently a prohibitive obstacle to increased deployment of inverter-based resources e.g. wind and solar PV. The reliance on inertia stems primarily from the wide-spread use of synchronous generators.

It has been proven that high shares and even 100% of IBRs can be possible in cases of small and large islands [86]. Nevertheless, the maximum level of renewable penetration without risking the grid reliability has yet to be further analyzed. The data available from grids with more than 50% electricity generation derived from IBRs (e.g. Texas ERCOT grid) are very promising. Already tested technologies have shown that high shares of wind and solar PV power are possible without the negative effects traditionally associated with diminished inertia [86, 87].

Further research is needed to acquire deeper understanding in aspects and scenarios not fully yet analyzed. New approaches and techniques may be required to maintain system frequency and reliability when integrating higher shares of IBR generation. At present, the coexistence of fast response inverter-based generators and renewable energy resources with synchronous allow for very high penetration levels of renewables without the need of new technologies and techniques [86].

4.3.3 Grid Codes and Regulations

The grid code, also known as transmission code in some countries, is a set of technical rules developed by a system operator (TSO) that define the conditions and technical requierments for any entity that connects to the grid [88].

Apart from the grid codes though, there are policies decided by policy makers and regulations applied by authority bodies (regulators) that crucially affect the development of renewable energy integration in every national power grid of each country. Therefore, the requisite initiatives and policies taken up by governments may trigger the swift growth of renewables and the appropriate regulations may further facilitate the investments needed for the development of renewbles. Also, the regulations can be the catalyst for advanced grid codes implementation that help the integration of new technologies, improve the grid reliability and optimize the benefits for all.

Advanced Grid Code capabilities

An example of an advanced grid code is the IEEE 1547TM-2018 Standard (IEEE 1547 for short) that incorporates many advanced capabilities for grid supportive functionalities (not included in previous versions of the standard), such as voltage regulation, frequency regulation, voltage/frequency ride through, advanced communications capability, control functionality etc. Moreover, ancillary services (as discussed in §4.3.2) can be provided even at the DER level.

It is compalsory that all newly manufactured inverters comply with this and other advanced standards. The utilization of these advanced capabilities is done by the new advanced inverters (aka “smart inverters”) and enables the improvement of power quality, facilitates the penetration of DERs and optimizes the grid operation as penetration increases [89].

The advanced grid code requirements allow the remote communication and control of DERs with the grid operator or an aggregator (a third party intermediary between consumer and grid operator) which can increase the situational awareness and tackle any problem whenever it happens [89].

When fully implemented the IEEE 1547 will bring about the following changes, among others:

- the ability of DERs to respond to grid contingencies.
- It will allow more DER assets to be connected to the grid (penetration increase).
- Communication protocol capabilities. Remote control of DERs via SCADA (Supervisory Control and Data Acquisition) or DERMS (Distributed Energy Resource Management Systems).

- Customers installing DERs may experience changes in their generation output under certain scenarios, which might require the adoption of new consumer protection measures [89].

It's important to note that all new capabilities and functionalities are disabled by default since the standard does not require any of them for back compatibility reasons but also because there are many different options available from which to choose.

The main reason that IEEE 1547 was initially drafted, is the voltage regulation capability. Any inverter-based DER that complies with this standard is able to participate in voltage regulation as currently do only transmission system facilities. Voltage regulation diminishes grid impacts and allows the connection of more distributed energy resources assets to locations where the voltage level of the circuit would otherwise be prohibitive.

Examples of IEEE 1547 functionality

In IEEE there are two available performance categories: 1) the Normal Operating Performance and 2) the Abnormal Operating Performance. The former determines how should perform regarding the voltage control during normal grid operation by specifying the available amount of reactive power for a DER asset to provide when needed.

The Abnormal Category determines the DER performance during contingencies such as transmission fault or generator loss by specifying the capability level of voltage ride through and frequency ride through. There are three sub-categories defined: I, II and III. Sub-category I is used only for DER assets that appear in low penetration in the grid such as flywheel storage systems; whereas sub-category III is intended for high penetration DERs.

Grid support functions

Traditionally, grid support functions (e.g. voltage and frequency regulation) were only provided by generation, load or storage facilities connected to the transmission system and by no means by DERs at the distribution grid level. However, this has changed and inverter-based DERs have the capability of providing such grid support functions.

It is not unusual that the voltage levels of certain feeder circuits are adversely affected by the high volumes of DERs. In these situations voltage regulation capability of DERs would be beneficial if activated. Other factors affecting the voltage level include: the utilities voltage regulation practices, the feeder design etc. Throughout a circuit there are locations with different levels of voltage; locations closer to substations and voltage regulation equipment have high voltage levels whereas the voltage levels are usually low when going away from such equipment.

Voltage Regulation

There are several functions that may be activated in order to regulate voltage, and thus help mitigate any negative impacts on the grid. Each of these functions interact with the grid differently and have differing impacts on the generation output of DERs.

The following are reactive power functions (included in IEEE 1547) that regulate voltage:

- Constant power factor mode (default): The power factor is set to a constant value. The power output may vary. The reactive power may be absorbed from or injected into the grid causing the voltage to decrease or increase respectively [89].
- Voltage-reactive power mode: The absorbed or injected reactive power is a function of the grid voltage level. This mode is meant to be used in cases where nominal voltage is desired.
- Active power-reactive power mode: The absorbed or injected reactive power is set to a constant value regardless of the active power output fluctuations of the DER.

The role of policy makers, regulators and utilities

Policy makers, regulators and utilities can define the grid code in a way that specifies whether of not certain grid supportive functionalities are activated or disabled (e.g. voltage regulation or frequency regulation etc.), which mode and what specific settings should.

If voltage regulations functions are to be used then it must be clear what mode, what category and what function settings should be adjusted from default values.

It is the responsibility of regulators and utilities to assess the interaction with interconnection procedures and the impact of the activated functions and whether grid upgrade is necessary for the DER connection to the grid.

The use of the aforementioned voltage regulation functions can enable the accomodation of more DER assets to be connected to the grid. Thus, the penetration of DER increases. Without these regulation functions, it would be necessary for the utility to carry out grid upgrades and the investors (i.e. producers) to pay for them. All these should be taken into account by utilities during the hosting capacity analysis.

Consumer impacts due to voltage regulation functions

Voltage regulation functions may result in real power generation reductions for certain DER assets due to reactive power production [89].

To address the potential impacts on DER producers, the utilities along with the regulators and policy makers must come up with ways to protect them. Regulators ought to keep balance between benefits of the grid and of the DER producers at the same time. The individual customer's DER investment should not be jeopardized in favor only the grid.

To address the issue, utilities and regulators are responsible to present a generally accepted and viable solution.

A proposed solution to consumer impacts

As a possible solution to the consumer impact due to voltage regulation functions as described in the previous paragraph, this study suggests the following scheme.

The utilities may apply a method which utilizes the smart meter measurements (and/or customer's inverter data) in order to calculate the loss of energy due to the specific voltage regulation function in use. Then the customer may be remunerated not only for the real power registered on the meter but also for the calculated energy losses (the active power which would otherwise be produced by the DER) using the same feed-in tariff per kWh. Such an incentive can readily be accepted by new customers when signing new solar PV agreements/contracts. Also, the current customers may accept signing a contract amendment which includes such terms and conditions. In any case, prosumers have nothing to lose since the compensation of energy whether injected or lost is always guaranteed.

A similar approach can be followed for the net energy metering solar PV systems; thus the billing mechanism takes into account the estimated loss of energy as well.

Additionally, (especially in case of existing DER customers' reluctance) an one-off amount of money may be considered for incumbent prosumers so as to accept a) the change of the inverters settings profile and b) the singing of the requisite contract amendment. In order for the one-off amount to be determined, regulators and utilities could make estimates of the benefits deriving from the use of the regulation functions, including the additional DER hosting capacity that is becoming available. That may result in different one-off amounts depending on the DER capacity and location. The latter factor should be levelized at the

broader possible scale (e.g. at country scale or on transmission system level) for equity reasons, since some DERs may be situated in more disadvantageous grid locations than others.

This flat-rate tariff for the provided grid support service and the produced energy, is both simple and reasonable; hence easily acceptable. The economic and moral justification of this scheme is that the prosumers must be compensated for the voltage regulation services they provide to the utility. The services provided to the grid result in generation loss (which would otherwise be injected into the grid), and therefore must be remunerated in an equal way as the real energy produced in order to allow a fair and equitable policy for all DER producers (either paticipating or not to voltage regulation).

Perspectives

Finally, it's worth noting, the voltage regulation functions can have optimal results at high DER penetration rates, when all or most of the DERs have enabled this function. If only a few DERs are participating in voltage regulation when most of them do not (as is the case with old inverters that do not provide the capability) then the effectiveness of the function is reduced. Additionally, in an already saturated grid where most DERs are non-voltage regulating, even new DERs with voltage regulation-enabled inverters cannot be connected to the grid.

Hawaii is an example of such late-stage adoption of voltage regulation. It has been estimated that if the old technology inverters had voltage regulation capabilities, the grid could host more DERs (penetration increase) [90]. An ongoing project in Hawaii aims to adopt energy storage systems and solar stations with advanced inverters that have grid supportive capabilities in order to multiply the number of private-owned rooftop systems [90]. This a great example of the benefits of incorporating new technologies to increase the DER penetration rate in an already saturated grid.

Conclusions

To make the most out of grid codes and regulations and achieve high RES penetration, regulators and utilities have to enable the usage of voltage and frequency regulation functions. Without these functions, the effectiveness of increasing the hosting capacity of the grid may be restricted.

Enabling advanced functions for DERs will help to accommodate more DER assets. In some cases, circuit location-specific inverter settings may be the only way for new producers to connect to the grid without the need of grid upgrade, which would otherwise be necessary if the inverter had no advanced capabilities (i.e. in case of no location-specific settings).

These functions may reduce more or less (depending on the circuit location of the DER) the generation output of a DER, which can have a negative impact on the viability of the consumer's investment. Customers protection measures should be considered.

As a contribution, this study proposes a specific, simple, fair and equitable solution in order to address the adverse impacts of the introduction of voltage regulation functions, and thus protect the distributed energy producers.

4.3.4 Energy Storage

Energy storage is a great tool that can enable high shares of renewables, especially variable ones such as solar and wind.

Energy Storage Technologies (EST) and the ensuing Energy Storage Systems (ESS) are essential to implementing high generation shares of RES. Although variable renewables cannot be treated in a dispatchable way, its unpredictable power output can be compensated not only by forecast information systems but mainly by the use of energy storage facilities.

Even a relatively small grid of a few dozens of GW in power (e.g. 10 – 40 GW) would require a GW scale energy storage system to compensate the unpredictability of variable RES and securing its operation for hours. E.g. to secure 3 GW for 2 days, a 144GWh storage system is needed.

ESTs facilitate the balancing of energy production and consumption and therefore enable the increased implementation of variable renewables.

The risk of the duck curve effect and over-generation can be mitigated and even eliminated when solar energy generation is combined with energy storage systems. Also, curtailment is not minimized when excess energy is stored for in order to be used later when energy demand peaks.

There is ongoing research by institutions and utilities that examines specific grid cases on how storage will better accommodate the increasing solar energy penetration without the obstacles associated with it [91].

Advantages of Energy Storage

Apart from being an enabler for high levels of VRES, the Energy Storage has the following additional advantages when used appropriately:

- Minimizing grid constraint issues. The local storage of excess energy and its release when demand exceeds local generation, can limit the need for additional interconnections and transmission upgrades, thus diminishing many constraint issues. In other words, it often happens that surplus energy is available but the cables transferring it are already at full capacity and therefore certain RESs have to be curtailed [92].
- Reduction of spinning reserves requirements. When implementing energy storage systems, it becomes possible to reduce the spinning reserve requirements and the subsequent costs can be used for energy storage systems investment [93].
- Flexibility improvement. The flexibility introduced to the grid by the storage systems limits the supply and demand imbalances related to high levels of VRES integration, which in turn promotes the energy transition.
- Pumped hydro can be considered as water batteries for variable renewables.

Energy Storage Technologies

The available storage technologies are briefly discussed in the following paragraphs, namely Batteries, Pumped Storage Hydropower and Hydrogen.

Batteries

Electricity storage refers to the various available technologies than can absorb electrical energy, store it as as different type of energy (e.g. chemichal, potential etc) and release it as electricity at a later point in time. Traditionaly the electrical energy was not stored and that's why the constant maintenance of balance between supply/generation and demand/consumption was always of utmost importance for power systems. However, Pumped Storage Hydro can be considered the only traditional systems to be used in practice for storage, although rarely.

In recent years, the interest in electricity storage has grown significantly as a means to enhance the power system flexibility. Once a very expensive technology, the cost of battery storage is gradually declining, rendering it a possible candidate for short-term timescale usage. Battery systems are not considered suitable for seasonal storage in the foreseeable future since alternative technologies are much more appropriate.

When existing traditional power plants are coupled with BESS (hybridization) by means of retrofit investments, then flexibility services can be provided. Even VRES can give flexibility services if combined appropriately with BESS provided that appropriate policy and regulatory frameworks are adopted.

Conventional power plants used to be the main source of power system flexibility since their ancillary services were used to balance supply and demand. Supply and demand variability and uncertainty in current power systems need conventional power plants' flexibility capabilities even more so.

A key strategy to enhance their flexibility is the coupling with BESS which is a viable solution not only in technical but also in economic terms [81]. For example, the existing gas peaking power plant in Norwalk, Southern California, which has been coupled with a 10MW/4.3MWh BESS. The plant offers spinning reserves and frequensy response ancillary services. The BESS component offers spinning reserve services for a few minutes period until gas turbine starts up and then the generator can reach full capacity output whereas the BESS output declines.

Pumped Hydropower Energy Storage

Pumped storage hydropower (or "pumped hydro" for short) is a renewable and clean electricity storage technology that can store excess energy from solar and wind power systems.

Pumped hydro is a peak-load energy resource which exploit the potential energy of water stored in an upper reservoir when there is excess energy in the grid. When the demand cannot be balanced by other generation assets, then water is released to a lower reservoir via turbines to generate electricity.

The amount of energy stored in a pumped hydro plant depends on the water capacity of the upper and lower reservoirs. The power generation depends on the turbine size.

As an example, one can refer to a facility with reservoirs of Olympic swimming pool size. If their altitude levels have a 500m difference then capacity power could be 3MW and the storage energy about 3.5MWh.

Two technologies of pumped hydro exist:

- Open-loop: either the upper or the lower reservoir is linked to a natural water stream (e.g. a river).
- Closed-loop: there is no connection to a natural water stream. The stores quantity of water is first pumped to the upper reservoir and then released to the lower one when needed.

Total pumped hydro capacity accounts for more than 94% global energy storage capacity. It's by far the largest battery technology as compared to any other storage technology. The total worldwide storage capacity is estimated to be 9000 GWh with potential for further increase.

Apart from flexibility through storage, pumped hydro also provides inertia, voltage and frequency regulation, and black start services. These capabilities are particularly useful in the light of the ever-growing penetration of renewables.

Other important characteristics are the long duration of discharge and the high power output which can reduce bottlenecks and the need for curtailment, as well as costs and GHG emissions. Additionally, it has a long life-cycle, low operational cost and does not depend to raw materials [94].

Currently, it is the only storage technology that can practically help achieving the ambitious 2050 Paris Agreement targets. Finally, the change of a traditional water reservoir facility to a pumped hydro has few environmental and social negative effects as compared to new hydroelectric plants [95].

In Greece, there are two operational and two planned pumped storage facilities. The following are namely the four pumped storage facilities in Greece (two operational and two planned).

- Thissavros dam. It's an open-loop hydro plant currently operational with generating and pumping capacity of 384 MW. The total energy stored is 3.82 GWh.
- Sfikia dam. It's an open-loop hydro plant currently operational with generating and pumping capacity of 315 MW. The total energy stored is 1.32 GWh.

- Agios Georgios dam. It's a closed-loop hydro plant under construction with potential generating and pumping capacity of 460 MW and 496 MW respectively. The total energy stored is expected to be 3.32 GWh.
- Pyrgos dam. It's a planned closed-loop hydro plant with potential generating and pumping capacity of 220 MW and 234 MW respectively. The total energy stored is estimated to be roughly 1.59 GWh.

Electric Vehicles

The widespread usage of Electric Vehicles (EVs) can enable decarbonization of transport and electricity generation sectors. The decrease of battery cost is anticipated to boost the EV market. The renewable fuels are considered as a better alternative for the heavy duty vehicle segment due to the batteries' low energy density.

Since the consumption and charging patterns are rather dissimilar, the stress to the electric grid is restricted. The EV charging takes place usually during the night [Figure 4.7] whereas the consumption peaks are in the morning and in the evening [96].

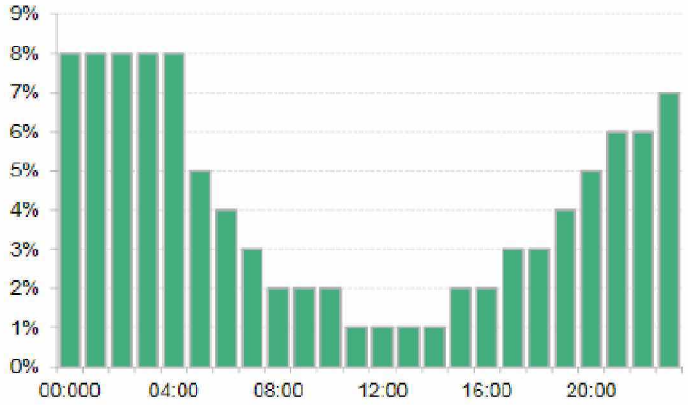


Figure 4.7 Typical daily distribution of EV charging (% of EV demand) [96].

A final important aspect of wide EV adoption is its contribution to energy storage. The development of cheaper batteries will enable the EV integration in the transport sector. The charging of EVs via charging stations can offer plenty of extra flexibility to the grid in the same way that any other storage technology would do. If the majority of the conventional light duty vehicles were to be replaced with EVs then the available storage capacity would offer a lot of flexibility to the grid. This would be the case if EVs were to be connected to the grid during the mid-day when the solar generation is at its peak. Connection to the grid in the evening when the demands peaks would time shift the solar PV production [96].

Hybrid Renewable Energy Systems

A Hybrid Renewable Energy System (HRES) combines diversification of generation resources and storage devices in a single system, thus improving the reliability as compared with other VRE systems which depend only on a single source and therefore are variable and cannot guaranty high availability supply.

The idea of a HRES was initially developed from the Hybrid Energy System (HES) which included at least one conventional, non-renewable generator e.g. diesel combined with a battery energy storage system (BESS). The idea of combining non-renewable and renewable energy sources has ultimately evolved to include 100% renewable systems (e.g. solar and wind) combined with one or more storage technologies e.g. batteries, fuel cells and supercapacitors.

Although the first HRESs were low capacity off-grid systems, nowadays systems of several megawatt capacity at MV are available for grid-connected high availability services [97].

In Figure 4.8, a typical Hybrid Renewable Energy System combines multiple energy sources to deliver non-intermittent electrical power.

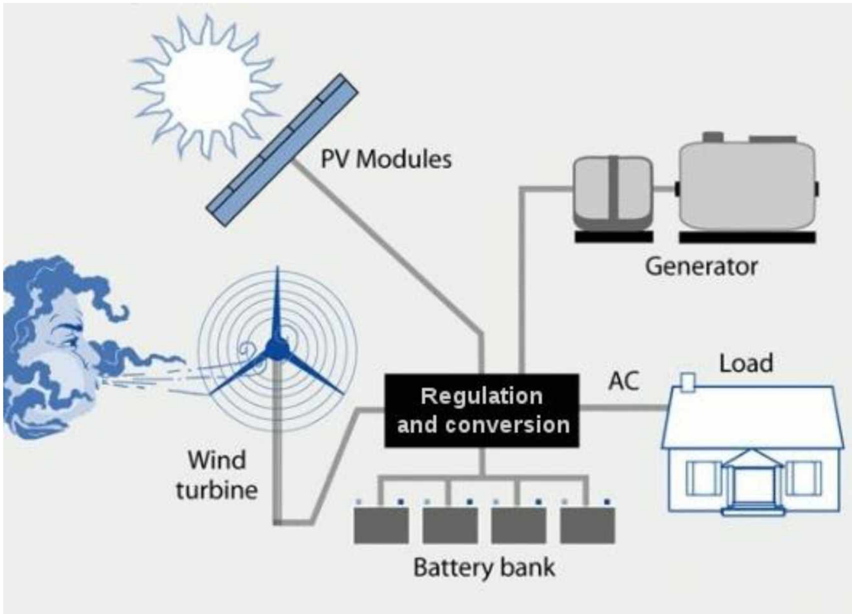


Figure 4.8 A common design of a Hybrid RES [97]

Even though the initial idea of HRES comes from off-grid installations, they can also be of benefit when connected to the distribution grid. These systems provide the benefit of storage in comparison with the conventional VRE systems which depend only on one source.

Hybrid systems will probably generate electricity when it is needed because:

- the peak generation hours for solar and wind systems are uncorrelated and usually happen in different periods throughout the day and the year, and
- whenever neither wind nor solar generation is available then power can be provided via storage systems.
- In the extremely rare case that none of the above is available (e.g. batteries have run low), HRESs can include an engine generator of conventional fuels (e.g. diesel) to provide with power and/or recharge the storage system.

Adding a conventional engine generator makes the system less green and clean but ensures availability and uninterruptible supply. Also, the system becomes more complex, but modern advanced electronics have overcome the technological issues of the past.

The most important aspect of the HRES design is the sizing/dimensioning of the capacity of its components. The wind and solar capacities of the installation site on one hand, and the percentage of the desired supply availability and the cost of the overall hybrid system on the other, will finally determine the storage capacity and the use or not of an engine generator. For instance, the storage capacity is typically sized so as to supply the load for one day. The right combination of the components' specifications can be customized for each particular use case so as to be efficient [98].

Hydrogen Energy Storage

Hydrogen energy storage is a green and sustainable storage option capable of providing flexibility.

The main characteristics of hydrogen storage are:

- the large, grid-scale storage capacities,
- the long time periods of storage and
- the lack of location restrictions.

The aforementioned attributes facilitate the energy transition. Specifically, the transition towards higher shares of VRES tends to destabilize the balance of supply and demand. However the excess electricity could be utilized to produce hydrogen through electrolysis and store it for long periods of time until VRES supply shortfalls occur. In such cases the stored hydrogen may be utilized to produce electricity and restore balance between supply and demand [99].

The electrical power grid needs to constantly balance generation and demand at any conditions while diminishing the reliance on the costly spinning reserve, and this can be accomplished by increasing the energy storage capacity, thus rendering the implementation of ESTs fundamental in today's power grids.

The integration of Hydrogen Energy Storage allows:

1. the absorption of excess energy generated by VRES which would otherwise be discarded (e.g. via curtailment) and also
2. the supply of stored energy (conversion of hydrogen to electricity) when the energy generation is not sufficient to balance the demand.

The hydrogen energy storage technology

The hydrogen energy storage in the form of gas or liquid, is a storage of chemical energy for long periods. It is a non-location specific energy storage that can be used whenever needed. In Figure 4.9 a HESS is illustrated showing its main elements.

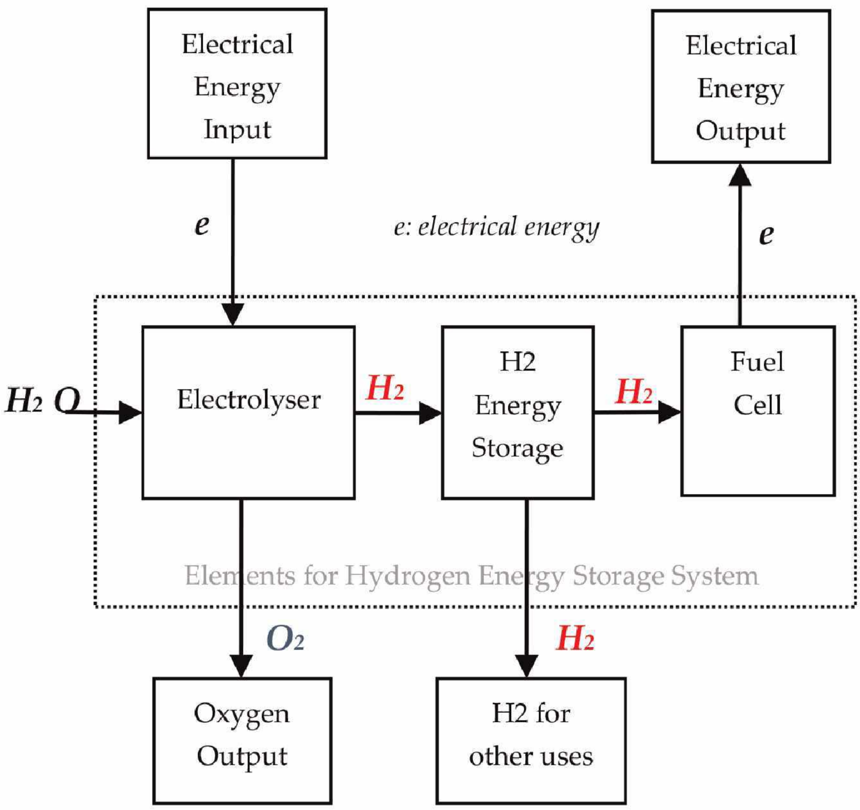


Figure 4.9 The basic components of a Hydrogen ESS [99]

When there is surplus energy from a renewable source, it can be stored in the form of hydrogen through a hydrogen generator which is called "electrolyzer". Hydrogen can be stored in various forms such as metal hydride, high-pressure gas and in Dewar tanks as liquid.

Finally, the stored hydrogen is converted back into electricity without any GHG emissions, and only heat and water are emitted as by-products. The fuel cell is the most commonly used technology to convert the chemical energy (i.e. hydrogen) back into electricity. Its convertsion efficiency factor ranges from 40% to 50% in practice. For comparison reasons, the maximum efficiency factor of a combustion engine is 37%.

An additional advantage of stored hydrogen is that it can be employed as a chemical substance (i.e. as a commodity) for uses other than producing electricity, offering further flexibility [99].

4.3.5 Curtailment

The term "curtailment" refers to the removal or reduction of power production (generation curtailment) when there is excessive electrical power in the grid. Power production is usually curtailed when the electrical grid is under unforeseen stress and there are no available alternatives to balance the grid. However, scheduled maintenance works and random malfunctions on power production assets are not considered as curtailment.

Generation Curtailment intends to minimize the stress on the grid components during certain periods of time. Most frequently, curtailment refers to the removal of VRE systems from the electrical grid.

Less frequently, curtailment may also refer to the Load Curtailment. In this case, load curtailment may seem similar to Demand Response, although it refers specifically to the removal or reduction of electrical loads (usually industrial loads) for a short period of time which is dictated by the electrical grid operators (i.e. TSOs and DSOs). Grid operators are able to cooperate with certain industrial consumers for curtailment (reduction) of electric consumption on short notice peak demand periods. These load curtailment services may be unscheduled or scheduled. The so-called Partners (industrial consumers) receive reimbursements for offering such services to the grid.

The Grid Operators' responsibility

The grid operators (i.e. TSOs and DSOs) are responsible for curtailing wind and solar generation systems according to specific contracts and regulations. The loss of energy that would be potentially generated cannot be compensated at a later period since the wind and sunshine are forever lost during the curtailment and they hadn't been exploited when available. That isn't the case for fossil fuels power plants because they can catch up later with the always available fuel (and not previously used; be it gas, coal or oil). As previously mentioned, the loss of power due to curtailment is usually considered as an extra service provided by the VRE system and therefore the producer is remunerated.

Usefulness of Curtailment

Curtailment can be used as a means to solve two different problems in the grid.

1. Local Congestion. In the case of local power congestion (aka "bottleneck" or "grid congestion") in the grid, generation curtailment is used to lift the congestion. That is, the power generated ahead of the congestion is curtailed. A grid congestion takes place when an overload prevents electricity from reaching the consumers. In this situation, other electricity generation assets (e.g. conventional power plants) that are behind the congestion, can be activated (if available) to resolve the issue.
2. Frequency Restoration. On the transmission grid, when frequency needs to be controlled but all other measures are exhausted (e.g. control reserves, spinning reserves etc.), generation curtailment can be used to restore the frequency to normal level.

It is important to note that one of the reasons for curtailment is the unpredictable nature or more accurately the deviation from the prediction of VRES power generation and power consumption assets. This prediction deviation of both VRES generation and consumption assets causes imbalances in the grid and/or local bottlenecks that can be resolved by curtailing excessive VRE power generation. So, the root causes of generation curtailment include not only the unpredictability and variability of VRE sources but also the inability of the electricity grid to transmit the surplus electricity power from VRE systems to consumers [100].

Energy curtailment is no longer considered as a rarely occurring event both in distributed and bulk generation (i.e. transmission) systems. The ever increasing penetration of RESs produces major technical challenges for transmission and distribution grid operators. Current electrical grid regulations impose the priority use of RESs' produced energy. Nevertheless, because of the variable nature of renewables, the operators often have to curtail certain amounts of generated energy by RES systems. Such power curtailments are necessary to take effect because the operational reliability of the electrical grid must be secured in all circumstances.

Shortcomings of Curtailment

In many cases, there is no practical nor feasible alternative to curtailment for the grid operator. Otherwise, power outages or a regional blackout may occur with serious consequences, economic or other. Therefore, curtailing is a very useful and effective tool (in terms of grid balance management) at grid operators' disposal to ensure uninterruptible electrical supply.

Nevertheless, the generation curtailment of VRE systems is inefficient and economically wasteful. The inexpensive electrical energy from environmentally friendly renewable energy sources is completely lost and cannot be compensated at a later period of time.

Consequently, curtailment is green energy wasteful means of grid balancing, but necessary in cases of imminent grid instability [100].

Taking into account the increasing shares of wind and solar power production, the curtailment rate is expected to increase in the future as well, so as to sustain the quality of energy supplied [101]. High rates of curtailment are uneconomical because a considerable part of the installed power capacity goes to waste when not used. Although curtailment is a useful tool, it should be used in a prudent manner.

How to Avoid or Reduce Curtailment

Extensive and inefficient curtailment can be avoided or at least reduced in an accepted level by utilizing certain solutions. The feasibility and the mix of these solutions depends on the specificalities of every national transmission system and distribution grid, so they have to be assessed, planned and implemented for each individual case.

The main solution options are i) Grid Extension as referred to in §4.3.1, ii) on-site storage (ref. §4.3.4) and iii) Intelligent Grid Management through Demand Response & Transactive Energy (ref. §4.3.6).

1. Grid Extension (aka "grid expansion"). This is the main tool the grid operators have at their disposal to first tackle the inefficient curtailments. The extension of the electrical grid prevents bottlenecks in the grid and enables more power to be transferred (Figure 4.10). Thus, expanding the existing infrastructure by adding power lines or replacing with the existing with higher capacity ones is a very effective and beneficial solution in the long term. The prohibitive investment cost and the long implementation time are the two main shortcomings of grid expansion.

2. On-Site Storage. When the previous option is not available the on-site storage may seem appealing as a quicker-to-implement alternative. Instead of transmitting excess power through HV or MV lines, it can be stored locally (on-site) in a battery bank or in the form of hydrogen via an electrolyzer. The main issue here is the long time required for the return of investment.
3. Intelligent Grid Management. It is a general term embracing Demand Response, Transactive Energy (e.g. blockchain enabled) and other demand-side technologies. The excessive curtailment can be reduced by managing the grid components in a smart way. Demand response schemes, time-of-use tariffs and decentralized storage systems (e.g. EVs) are some of the potential options [100].

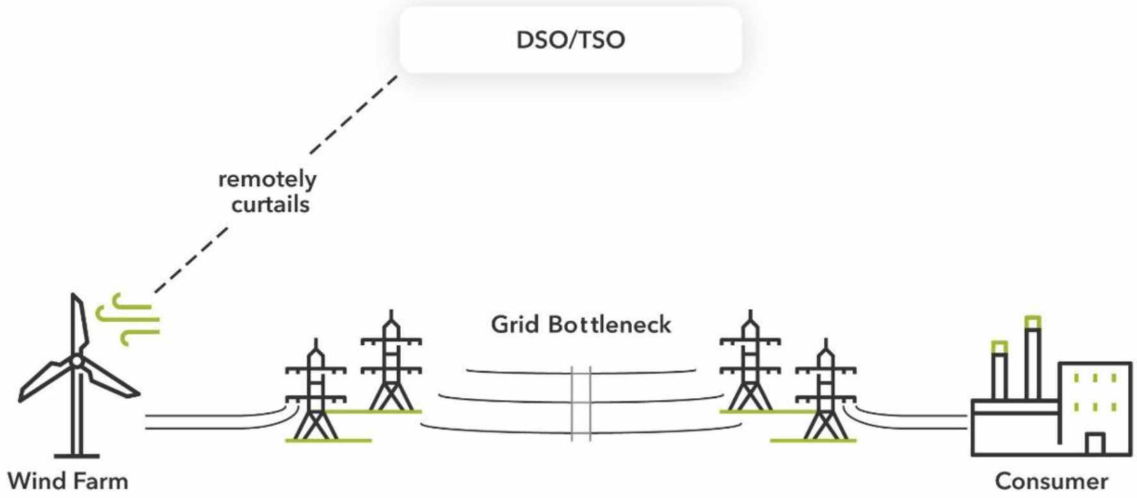


Figure 4.10 Example of curtailment of VRE systems due to grid bottleneck [100]

Compromise between Grid Expansion & Curtailment

This compromise between the level of grid expansion and the rate of curtailment (taking also into account the amount of curtailed energy) needs to be calculated and estimated for each specific situation (national and regional grids) so that only the necessary grid expansions are planned and implemented.

Curtailment at low levels are considered normal and not of a problem in system operating menagement. It doesn't make economic sense to construct all the transmission infrastructure and energy storage that enable the utilization of all renewable electricity produced. While levels of curtailment rise, the right trade-off between grid expansion, storage and costs (operational and investment) has to be achieved.

RES Curtailment and Storage

High rates of RES curtailment can be constrained when energy storage systems (ESS) are installed to store the excess energy generated by RES during periods of low demand. The stored energy will be released to the grid at the times of high demand and/or low RES production.

Energy storage improves the efficiency of energy generation and separates production from consumption (at least to a certain extent) for the first time since the inception of the electrical grid in the late 19th century. The requirement for absolute balance between energy supply and demand has not to be as strict as in the past and temporal shifts of energy needs are possible nowadays.

The combination of VRES with energy storage systems can be beneficial not only to the grid (i.e. reliable operation) but also to the environment, since less use of fossil fuel generation is needed. Widespread use of ESSs will in turn spur further penetration of RESs and minimize the relience of imported fossil fuels.

4.3.6 Renewable Energy Forecasting

The efficient harvest of variable renewables, mainly wind and solar PV, requires the appreciation of the variability causes and also the capability to anticipate many atmospheric procedures in a wide range of temporal and spatial scales. The knowledge of the physics of atmosphere and its dynamic nature which actually cause the wind and affect the weather, hence determining the solar resource, is important to modeling and forecasting for the renewable resources [102].

Among the new tools and practices that attempt to deal with the variability and uncertainty of wind and solar renewables, is the forecasting of their expected generation output. Wind and solar forecasts are widely used by power system operators (primarily TSOs) to schedule generation, procure operating reserves and secure sufficient flexibility to accommodate for changes in output, that is, forecast errors [103].

For example, a TSO may turn off several thermal power plants (e.g. coal and natural gas plants) for a few days based on VRE forecasts and thus rely on green and clean energy sources [104]. The accurate wind and solar forecasts mean that it can be anticipated when there will be enough renewable energy to meet the power demand and therefore traditional fossil fuel plants can be powered off safely and thereby save money and reduce GHG emissions.

In the past two decades, the increasing research interest in VRE integration and forecasting has led to new forecasting techniques which reduce the uncertainty (forecasting errors) and as a consequence reduce the need for spinning reserves. Such regulation reserves were traditionally used for contingency purposes and random fluctuations. Due to intermittent and variable nature of wind and solar, additional reserves could be necessary to address any unpredictable output outages. The amount of these additional reserves depends to a large extent on the accuracy of forecast. New numerical prediction methods and statistical models have improved the accuracy of wind forecasts [105]. Short term forecasts (<3hours) of a wind turbine output can reach low error rates of just 5% (as a percentage to installed capacity). For medium term forecasts (about 24 hours), the mean error rate can be as low as 20% [106].

In Table 4.2 are shown the types of VRE forecasts in various time scales and relevant applications and methods.

Table 4.2 Types of VRE Forecasts according to various time scales, applications and methods (source: NREL)

	Type of Forecast	Time Horizon	Key Applications	Methods
Generation	Intra-hour	5-60 min	Regulation, real-time dispatch, market clearing	Statistical, persistence
Generation	Short term	1-6 hours ahead	Scheduling, load-following, congestion management	Blend of statistical and NWP models
Generation	Medium term	Day(s) ahead	Scheduling, reserve requirement, market trading, congestion management	NWP with corrections for systematic biases
Generation	Long term	Week(s), Seasonal, 1 year or more ahead	Resource planning, contingency analysis, maintenance planning, operation management	Climatological forecasts, NWP
Decision Support	Ramp forecasting	Continuous	Situational awareness, curtailment	NWP and statistical
Decision Support	Load forecasting	Day ahead, hour-ahead, intra-hour	Scheduling, economic dispatch, congestion management, demand side management	Statistical

Forecasting involves many prediction techniques and can be categorized in the following classes [107]:

- Spatial Scale: single VRE station forecasting, regional forecasting

- Temporal Scale:
    - short term (up to 4 hrs),
    - medium term (4 – 72 hrs),
    - long term (4 – 52 weeks),
    - very long term (more than a year).

Although a significant progress has already been achieved regarding the renewable forecasting computational methods, there is still a lot of ongoing research on the matter and the improvement of their prediction accuracy.

Benefits of forecasts

The improvement of VRE output predictions permit grid operators to acquire a deeper understanding of the VRE production trends and improve their use. For example, advanced machine-learning algorithms by IBM improved the prediction accuracy by 30%. But as the VRE share grows, further enhancements in forecast accuracy will be needed [91].

The application of VRE forecasting is useful to various aspects of power system operations such as scheduling, dispatch, balancing and reserve requirements. The use of forecasting enables the TSOs to predict with significant accuracy the increase or decrease of renewables production so as to economically balance demand and supply in short and medium term dispatching. The benefits are the minimization of renewables curtailment, the reduction of fossil fuel usage and its costs, and the improved system reliability [108].

For example, a TSO may turn off several thermal power plants (e.g. natural gas & coal plants) for a few days based on VRE forecasts and thus rely on green and clean energy sources [104]. The accurate wind and solar forecasts mean that it can be anticipated when there will be enough renewable energy to meet the power demand and therefore traditional fossil fuel plants can be powered off safely and thereby save money and reduce GHG emissions.

Forecasting Methods

There are two main forecasting methods, namely the Physical Modelling and the Statistical Modelling. Usually, these methods are used in combination, that is, the results of the former are fed into the latter to achieve more accurate forecasts.

The Physical Modelling enters weather data (i.e. measurements of temperature, pressure etc.) to NWP models (Numerical Weather Prediction) to get results on weather characteristics.

These results may be easily converted into power output data. However, due to limited observational data and computational power, all NWP models use approximations in their numerical calculations. The resulting limitations and systematic biases of the forecast can be alleviated by using next the Statical Modelling.

The Statistical Modelling is based on historical and real-time production data in order to numerically adjust the output of the NWP model. Persistence forecasting is one of many statistical methods that is easy to implement, which considers that the present power production rates will continue to be the same, or else put, persist in the short term.

Ensemble forecasting is the good practice to improve forecasts by utilizing and comparing the results from many different forecast methods [108].

Applying VRE forecasts in System Operations

The application of the forecasting methods facilitates and improves the system operations at different time scales.

Medium term forecasts offer power predictions for a few hours up to the next couple of days. These predictions are helpful in dispatching power assets because they limit costs and inefficiencies that would otherwise result by the unnecessary start and stops of conventional thermal plants.

Intra-day forecasts supply with short-time interval power predictions (e.g. every 10 min) of up to about seven hours. This information is used for real time scheduling [108].

Finally, forecasts of decentralized generation (DG) could be merged with forecasts for demand to attain net-load forecasts. These forecasts provide a better visibility of demand-side variability. Net load behavior is more useful to a TSO because DG and load are indiscernible from the standpoint of the transmission system [108].

Conclusion

Forecasting can be deemed as the most cost effective technique for integrating VRE resources into the electrical grid. It should be stressed however, that it cannot be used as the one and only solution for high penetration levels but in combination with the previous methods and technologies to further improve the integration of renewables, reduce the generation costs and facilitate the decarbonization of electricity generation.

Chapter 5 Conclusions & Contributions

In the last decades, environmental concerns and specifically extreme climate change phenomena have come to the spotlight. Excessive greenhouse gases emissions have been held responsible for this situation and solutions have been put forward to combat the problem. The energy transition is considered the only way forward and it involves the transformation of the global energy sector from traditional fossil fuels dependency to net zero solutions within the next decades. A great portion of the energy sector is the electricity generation which is accountable for most of the CO_2 emissions and in order to become zero-carbon, high shares of renewables have to be part of the energy mix.

Renewable resources are evolving into the sources of the future. The rapid growth of renewables and the transition towards 100% renewable energy penetration, apart from the benefits, brings along challenges to the electric grid operations. Due to the interest on renewables, as of today, a lot of research has been conducted and many scientific papers have been published.

In this study, we have presented all the elements of the issue based on the rich research literature. The renewable energy resources and the electrical power system have been discussed, with an emphasis on the transition from the conventional power system to the smart grid, and the ensuing challenges of that transition.

Finally, we discussed all the latest solutions and developments that will help to achieve the 100% renewable energy goal, such as: the upgrade and extension of the transmission infrastructure, the ancillary services the renewables can provide, the significant role of grid codes and regulations, the great importance of energy storage that compensates the variability problem of wind and solar PV energy generation, the curtailment capability and its benefits, and finally the forecasting as a tool to minimize the unpredictable nature of renewables (mainly wind and solar).

Also, the important special role of the nuclear energy is highlighted, and we have given prominence to its significant contribution as a transitional source of base load energy.

One of the contributions of this study – regarding the application of regulations and grid codes – is the proposition of a specific, simple, fair and equitable solution in order to tackle the adverse impacts of the introduction of voltage regulation functions, and thus protect the distributed energy producers (§4.3.3). This proposed solution can be beneficial for both the utilities and the prosumers.

Another contribution of the study is the comprehensive presentation of the all the facets of the "Renewable Energy Integration to Smart Grid Energy Systems" with an emphasis on the operational challenges as well as on the proposed solutions. This study is particularly beneficial to policymakers (usually with low technical background) and other electricity market stakeholders because it provides and explains an overview of all the relevant issues in a persuasive and accessible manner. This can encourage the adoption of the available solutions and enable further the increase of renewables into the supply mix.

All these technologies, practices and regulations that have been discussed in this study, are promising solutions towards a smooth renewable energy integration and the elimination of fossil fuel reliance. However, some challenges for reliable and efficient high RES penetration still remain. The enhancement of the available solution tools and the right combination of using them for every specific situation, seems to be the final recipe of success.

The main conclusion of this treatise is that a penetration of 100% RES in the electric grid is attainable. The proposed solutions are intended to be used in combination since there is no single "cure-all" solution. Each one is appropriate for addressing a specific range of issues. All of them together will lead to the desired result of sustainable, flexible and reliable electrical grid. In other words, it is the appropriate mix, which depends on the peculiarities and specificalities of each transmission power system, that will result in a total viable solution. It's exactly these very distinctive characteristics that must be taken into account by the grid planners during their analysis.

Policy makers, regulators, utilities, researchers, planners and other stakeholders, should move forward swiftly by specifying the appropriate mix of solutions for each particular case, by adopting all the new technologies, practices and experience available as have been presented in this study. This is the only way to reap the benefits of the renewable energy integration into the smart grid energy systems.

The time is now to plan and implement a sustainable, clean and equitable energy future.

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