Contract No 727481 RE-SERVE

Deliverable 1.1

Scenarios & architectures for 100% RES and roles of sector actors

Contractual Date of Delivery to the CEC	31 Dec 2016
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Participant(s)	PoliTO, RWTH, TransE, CRE, UPB, EED,WIT
Workpackage:	WP1 – System Level Work for RES integration
Estimated person months	4 Person Months
Security:	Please chose: PU = Public
Nature	R = Report
Version	1.0
Total number of pages	97

Abstract

This deliverable provides an approach, based on a proposed multidimensional framework, for designing and consistently identifying energy scenarios characterized by high levels of RES penetration in electricity generation, up to 100%. We consider the foreseen scenarios for the evolution of energy systems worldwide as the starting point to identify the scenarios to be studied in the project, with special reference to the Romanian and Irish contexts, adopted in the project as use cases. We discuss the technical challenges in terms of operation of power systems under high share of RES and the contribution from ICT technology (presently and available in future). We consider the key-players, traditional and emerging, in the electricity arena and we list the “smart” functions especially related with the accommodation of high shares of RES in the electricity systems. A multidimensional framework, based on 11 different dimensions is exploited to define scenarios based on which we will define detailed use-cases. We identify 7 different scenarios, related to the two main research questions of the project (frequency and voltage stability) and to the two selected areas (Romania and Ireland) chosen for testing and demonstration of the concepts developed in the project.

Keyword list

RES penetration, DMS, synthetic inertia, Electricity industry Actors, Smart Grid Architecture Model, smart functions

Disclaimer

All information provided reflects the status of the RE-SERVE project at the time of writing and may be subject to change.

Executive Summary

This deliverable sets up a knowledge base to select and identify relevant high level scenarios corresponding to high RES penetration into the power systems, up to 100%. The increase of the share of electricity generation from renewables (both with/without mechanical inertia) poses crucial challenge to the operation and security of emerging electricity systems. Those challenges are addressed, in RE-SERVE, by two research questions related respectively to secure fast and flexible frequency and voltage control. The strategies and techniques to address these challenges need to be tested and demonstrated with reference to sound and meaningful scenarios based on the two considered geographical areas of Romania and Ireland. A set of well-formalized scenarios is the basis for defining and implementing, in a simulation environment, detailed use-cases for testing and demonstrating control techniques.

The scenario definition needs a formalized approach to assure the clear representation of each scenario in terms of a collection of various elements identifying a unique set of assumptions for the study. We proposed a multidimensional framework for this purpose. Our framework is composed of 11 dimensions (abbreviated as “D” below) divided into 4 groups:

1) *System information* (D1 Generation, D2 Transmission, D3 Distribution, D4 Utilization)
2) *Sub-scope of analysis* (D6 System states, D9 Time frames, D10 Power system model
3) *Emerging functions* (D5 Nature of inertia, D7 Smart Functions D11 ICT for power system)
4) *Actors* (D8 Actors involved)

We describe each dimension with a set of sub-dimensions:

- *D1* is articulated in bulk and distributed level,
- *D2* in HVAC, HVDC and Hybrid,
- *D3* in connected to HV and islanded,
- *D4* in consumers, prosumers, EV and storage,
- *D5* in synthetic inertia, mechanical inertia and mixed,
- *D6* in normal, alert, emergency and restoration operation,
- *D7* in advanced metering, building automation, real time info, fault analysis, distribution management system and advanced automation,
- *D8* in TSO, DSO, regulator, retailer, prosumer, consumer, load aggregator, EV stations and virtual power plants,
- *D9* in timeframes from micro seconds to tens of years,
- *D10* in steady state, dynamic and transient and, finally,
- *D11* in information and communication.

With reference to the two research questions, the two geographical areas and applying the proposed multidimensional framework, we identify, without ambiguity, 7 scenarios (5 for frequency studies and 2 for voltage studies).

The *scenarios identified for frequency study* are:

- SF_A1) Mid-term probable, still fossil (not 100%RES, with still CO2 generation parts).
- SF_A2) 100%RES mostly wind (wind generation, bulk storage with HVDC connections and a medium level of prosumers)
- SF_A3) 100% RES mostly PV (PV generation, distributed electrochemical storage, HVDC connections and EV/V2G).
- SF_B1) 100% RES, fully synthetic inertia (wind farms connected to transmission, distributed generation connected to distribution system).
- SF_B2) 100% RES, mixed inertia for frequency (wind, solar and storage plus hydro/pump hydro, bulk generation connected to transmission, distributed generationconnected to distribution)

The *scenarios identified for Voltage study* are:

- SV_VA1) 100% RES (distributed generation and fully synthetic inertia)
- SV_VA2) 100% RES (distributed generation and mixed mechanical/synthetic inertia)

The expected evolution of energy and electricity systems world-wide, with special reference to the penetration of RES, provides a reference for scenarios design. We considered 7 future world energy scenarios based on predictions from the European Commission, Word Energy Council, Global Energy Interconnection Development and the Cooperation Organization. Total primary energy supply will increase but at a reduced rate of increase, lowering for all scenarios the energy intensity of the world of 30/40% in 2050 with respect to the 2005 baseline with 50%. In these scenarios electricity will become much more importance as a source of power and final electricity consumption will increase in all 7 scenarios, from 2 to 6 six times of the baseline value, making of paramount importance a secure operation of the grid. The share of RES in electricity production in 2050 varies between 20 and 70 % according to various scenarios.

In the EU policy documents, none of the current EU policies directly target 100% RES by 2050. In fact, although a 2050 goal of reducing greenhouse gases by at least 80% is stated, nuclear power plants for base load and gas fired plants will still survive due to their relative lower impact and high flexible capacities. Also coal power plants especially with Carbon Capture Storage (CCS) technologies will continue to exist. However, wind will become the first source of energy both in terms of installed capacity and energy produced. In reference scenario, RES penetration will reach up to 50-55% in 2050. In some reported research and projects, several non-governmental bodies assumed scenarios for 100% decarbonized systems (with CCS and nuclear and 100% RES by 2050). In all those scenarios wind, solar and hydro sources account for more than the 85% of the installed capacity followed by geothermal and biomass sources. Romania is expected to reach just 40% RES penetration in 2050 due to the massive penetration of nuclear and low presence of PV, while Ireland will reach 60% penetration due to the enormous quantity of wind energy. Penetration of renewables to 100% is not yet foreseen. New actors and functions will facilitate the accommodation of electricity generation from RES in electricity systems both at transmission and distribution levels.

New “smart” functions are emerging in electricity systems and the main goal is to facilitate the integration of renewable energy sources (particularly of the stochastic sources such as wind and solar energy) and therefore to avoid the consequent massive investment in transmission and distribution network infrastructure, which is highly costly and not favored by local populations. All new functions introduce new form of storage and new flexibility capabilities into the grid. The most important will be the introduction of new forms of short term, medium and long term energy storage to permit the system to collect and store energy and be secure even in the long term absence of power from renewable primary energy sources. Secondly, the load, historically highly stochastically, will introduce new technologies to control its behavior and will become more flexible. Finally, the RES will be requested to provide services to the grid.

The main shift in the corresponding roles is the new central role of the DSO, which will have to manage its grid not in passive way like in the past, but in a manner more similar to today’s TSOs. New form of strict cooperation between TSOs and DSOs will be needed to avoid non-secure operation of the grid. The focus of policies and research is on finding the best technical and regulatory solutions for managing high RES grid. Finally, prosumers and load aggregators will enter the electricity sector representing the new flexibility capacity of the loads.

The ICT technologies, especially related to the forthcoming 5G mobile systems, provides new low latency, high availability and reliability, high speed and both wideband and narrowband communication facilities for the implementation of the coordination of RES generators under low system inertia. 5G systems will be available on the global market from 2020 onwards and the system has been designed with the needs of Internet of Things applications, and industrial automation applications in particular, in mind.

This deliverable is organized as follows:

- From chapter 2 to chapter 6 we build a conceptual framework to characterize high level scenarios of RES penetration. We gather a theoretical knowledge on the problems and solutions linked to high RES penetration grid with reference to the two research questions of the project. In chapter 2 we conduct a survey of road maps towards energy future scenarios, in the electricity sector, in line with the climate policies from the world level, the EU level down to the national levels (Romanian and Irish cases).

- In chapter 3 we identify smart functions both at the transmission and distribution level, further their corresponding roles are mapped either to the emerging players or conventional players in the system.
- In chapter 4 we briefly introduce the system frequency and voltage stability issues; current practices and future control architectures are also discussed respectively for these two issues. In chapter 5 and 6, possible information architectures and services and consequent technologies of the communication systems, as a backbone system for power systems, are introduced and compared in general. New communication technology, such as 5G, available from 2020, can be used as an enabler for new possibilities for power system controls.
- Chapter 7 and 8 are the core of the deliverable; there, starting from knowledge developed in the previous chapters, we provide a multi-dimensional framework for a comprehensive understanding and designing of the scenarios and we identify 7 scenarios to be considered.

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1. Introduction

WP1 aims to lay the foundations for the next steps of RE-SERVE project. The project focuses on the possibility to accommodate high shares of electricity generated by RES, both with and without mechanical inertia, up to 100 %, addressing two main research questions related respectively to secure fast and flexible frequency and voltage control. New control strategies will be devised starting from the development of new research concepts to be implemented and validated through the use of extensive simulations and real test beds provided by Irish and Romanian networks operators. One of the main focuses of the project is on the testing of future ICT technologies to enhance RES controllability and grid management. These elements form the objective and the initial requirement of the project.

WP1 provides the general frame of the project defining, through a proposed multi-dimensions framework the high level scenarios to be considered for the testing and demonstration of the approaches that the project will propose for answering to the research questions. Based on those scenarios detailed uses cases, to be implemented in the simulation platform, will be developed and detailed in the next deliverables. The theoretical study of new control strategies will be the focus of WP2 and WP3 while the implementation and verification of these new concepts will be done in WP4 and WP5. Finally, in WP6 we will propose new elements in the definition of European network codes for allowing the accommodation of high share of renewables.

Figure 1 represents the working structure of WP1, linking concepts to be considered and output to be produced with tasks and deliverables of the work package. We proceed from a high level qualitative perspective toward a very detailed quantitative one, in which the use cases for simulations are defined. We start considering, in task 1.1 and 1.2, a reference framework as a basis for the designing the scenarios on which the project will focus. The reference framework consists of an overview of internationally accepted evolutionary energy scenarios with special reference to RES exploitation (chapter 2), of a survey of the main technical challenges in accommodating RES (chapter 3) and of a ICT reference about communications technologies for allowing the implementation of new control techniques (chapter 5,6). From the knowledge of the framework we proceed to a precise and formalized scenario design through the definition of a multidimensional framework that is also mapped into Smart Grid Architecture Model [1] (chapter 7). This framework is able to specify all the characterizing elements in a scenario of electricity generation by RES. The multidimensional framework then is applied to the identification of a set of scenarios relevant for the project that are presented and discussed (chapter 8). The outcomes of those activities are reported in the present deliverable (D1.1).

Then we will resort to SGAM methodology to further detail the scenarios in a coherent and consistent way. SGAM methodology, thanks to its systematic matrix approach, will clarify all the technological, functional and ICT requirements which will have to be mapped on the grid domain and zones. In particular, in task 1.2 (D1.2), the main focus will be the Function and Component layer, while in Task 1.3 (D1.3) the main focus will be on Information and technological layer. Finally, in task 1.4 (D1.4), starting from the first Scenarios definitions and consequent mapping into the SGAM matrix, a quantitative representation of the scenarios will be performed in such a way to be able to provide practical use-cases related to Romanian and Irish context that will be used for the simulation part in WP2 and WP3. The use-cases will be therefore highly detailed and coherent with RE-SERVE initial requirements. A taxonomy will be added to the results to fix the meaning of the most important terms related to the study. In D1.5 modifications to the use cases will be considered following the results of others WPs.

It is important to note that every step in the WP1 will tend to progressively clarify and give content to initial requirements. This fact is depicted in Figure 1 by the arrow on the right which goes from an abstract level to a detailed one and by the different perspectives (reference, holistic,..) we are assuming moving toward the definition of the Use Cases. Figure 1 relates the conceptual framework to each chapter of this deliverable as well.

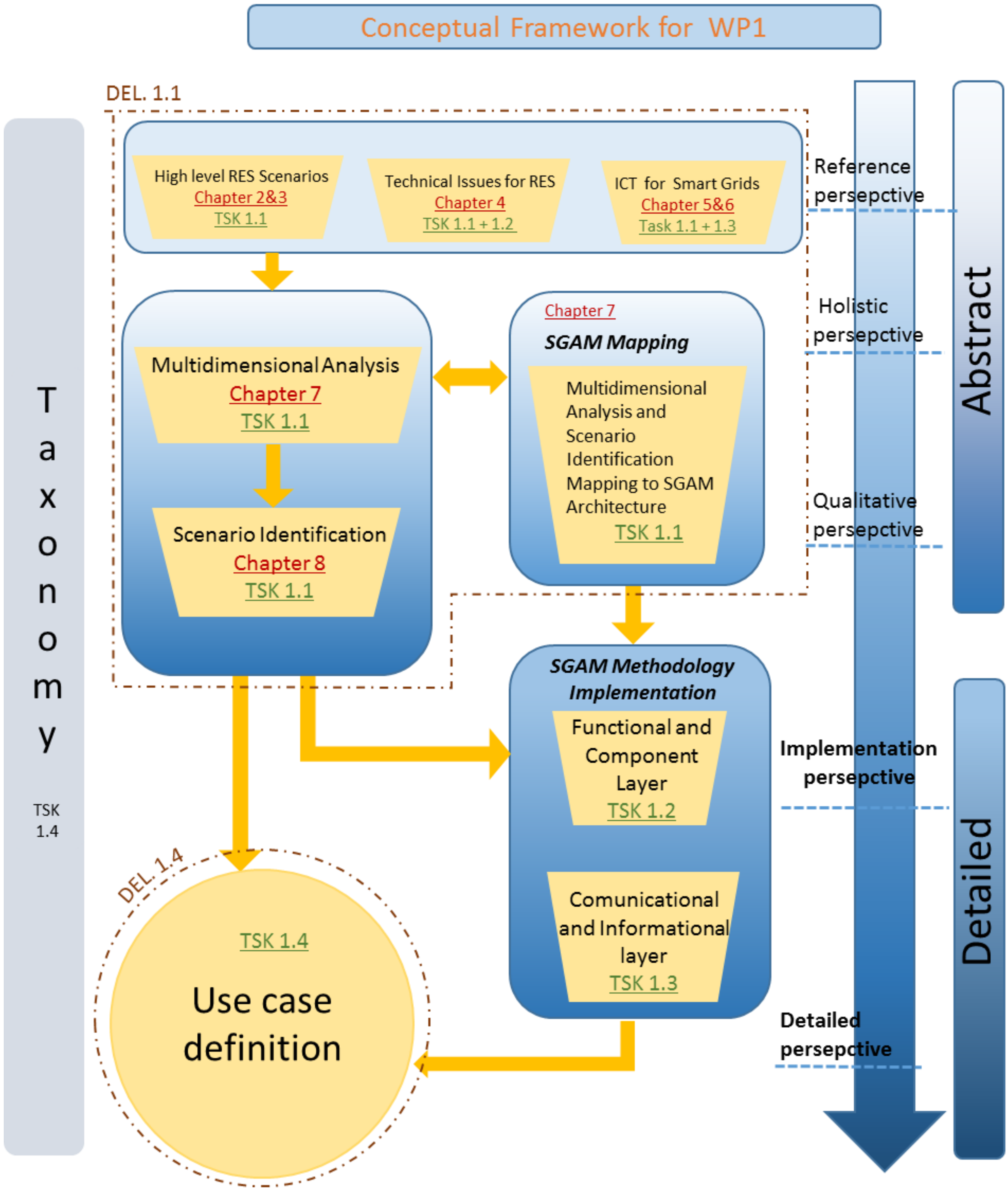


Figure 1 Conceptual framework for WP1 and D1.1

2. Perspective on emerging scenarios for energy

This chapter aims to provide a survey of high level perspective on energy scenarios with special focus on RES penetration. In this chapter, starting from an overview of the emerging scenarios in the world, the energy perspective in the EU with a focus on the electricity sector is discussed, and finally the trends and perspective in two member states of EU, Ireland and Romania, are presented to provide a vision of the RES penetration in those Countries. This survey is intended to present the RES integration trends and regulation-based roadmaps in the world, and especially in the EU, to fit our scenarios in a wider perspective.

First we analyze the scenarios for the world energy utilization, which can be used as a reference for the energy perspective at EU level. Secondly, EU energy reference scenarios are established with several published projections, including EC reference scenarios of the SET-Plan. Studied from E-Highway, European Renewable Council, European Climate Foundation, towards 100% RES in the electricity sectors are introduced as well. Thanks to the rapid development of technologies for clean energy utilization and power transmission, the scenario for future energy use is striving to meet the governments' policies and public's expectations for sustainable and environmental-friendly developments. The share of renewables in power generation at EU level will get a stable rise according to all the scenarios, which is going to replace large shares of traditional fossil fuels and nuclear energy in 2050. Finally, the reference scenarios for Romania and Ireland are introduced as a basis for designing the specific scenarios in these two areas.

2.1 World energy perspective

The world energy scenario is established on the basis of projections regarding the current trend or some different assumptions on future constraints, like environmental awareness, policy intervention, technological trends etc. Seven reference forecasts will be analysed and compared in the following context [1].

2.1.1 World scenario description

The first two scenarios come from the World Energy Technology Outlook – 2050, European Commission, 2006 [3]. The WETO-H2 report places the European energy system in a global context. It is structured around a business-as-usual case, and features two specific scenarios that reflect the political will of Europe to be at the forefront of the struggle against climate change and to promote new clean energy technologies:

WETO Base: it is the "Reference case" that describes the developments of the world energy system up to 2050, and the related CO_2 emissions assuming **a continuation of existing economic and technological trends**, including short-term constraints on the development of oil and gas production and moderate climate policies for which it is assumed that Europe keeps the lead. Without determined action, energy demand will double and electricity demand will quadruple compared to 2001, resulting in an increase in CO_2 emissions. This Reference projection adopts exogenous forecasts for population and economic growth in the different world regions and it makes consistent assumptions for the availability of fossil energy resources and for the costs and performances of future technologies.

WETO CCC: the "Carbon Constraint Case" that explores the consequences of more ambitious carbon emissions policies that aim at the long-term stabilisation of the CO_2 concentration in the atmosphere. Early action is assumed in industrialised countries, while more time is allowed for the emerging and developing countries. This case reflects a state of the **world with moderately ambitious climate targets**, aiming at an emission profile that is compatible in the long-term with concentration levels pre-1990 levels.

Then we selected only two of the four scenarios from the Energy Scenario Development Analysis: WEC Policy to 2050, World Energy Council 2007 [4].

LG-LC: it is the "Low Government Engagement – Low International Cooperation and Integration" scenario. In this case, there is a rather **low concern about CO2 mitigation and energy efficiency everywhere**, which result in a rather high world energy demand despite a rather low world economic growth.

LG-HC: it is the “Low Government Engagement – High International Cooperation and Integration” scenario. There, the world benefits greatly from a successful economic globalization and a highly liberalized context for business and trade. The world’s economic perspectives are brilliant. Governments rely heavily on **private business for the development of energy systems and to create appropriate market conditions**. Policy concerns for energy efficiency and CO2 mitigation are boosted by the good international climate, but they nevertheless conflict to a certain extent with the short-term profit logic of private investors and their impacts are not sufficient to moderate growth of world’s energy demand, driven by the high economic growth.

Other two forecast come from World Energy Scenarios - Composing energy futures to 2050, World Energy Council, 2013 [5]. The elements of these two scenarios are generalised as being applicable to the entire planet. They are:

JAZZ: it has a focus on energy equity with priority given to achieving individual access and affordability of energy through economic growth. There is **a consumer focus on achieving energy access, affordability, and quality of supply with the use of best available energy sources**. Technologies are chosen in competitive markets and energy sources compete on basis of price and availability. Renewable and low-carbon energy grow in line with market selection. In the absence of international agreed commitments carbon market grows slower from bottom up based on regional, national and local initiatives.

SYMPHONY: it has a focus on achieving environmental sustainability through internationally coordinated policies and practices. A world where there is a voter consensus on driving environmental sustainability and energy security through corresponding practices and policies. Governments pick technology winners and selected energy sources are subsidised and incentivised by governments. **Governments actively promote certain types of renewable and low-carbon energy and carbon market** is a top down approach based on an international agreement, with commitments and allocations.

The last is **GEI** (Global Energy Interconnection) scenario [6], which refers to the development of a globally interconnected, ubiquitous robust super grid, supported by backbone UHV grids and dedicated primarily to the transmission of clean energy. Grids of different continents are linked in order to remove environmental and spatio-temporal limitations.

In the following section we compare these 7 reference scenarios in a time frame from 2005 to 2050, in terms of the different forecasts they made over the profile followed by the most important macroeconomics and energy quantities (like GDP, prime energy supply, energy intensity, etc.)

Table 1 Key-point for various Scenarios [1]

	WETO Baseline	**WETO CCC**	**LG-LC**
	• Continuation of actual economic trends • Continuation of actual technological trends • Exogenous forecasts for population and economic growth • Consistent assumptions for the availability of fossil energy resources • Consistent assumptions for the costs and performances of future technologies	• More ambitious carbon emissions policies • Moderately ambitious climate targets • Early action assumed in industrialised countries • Medium economic growth • Quite low energy demand	• Low government engagement • Low international cooperation and integration • Low concern about CO_2 mitigation • Low concern about energy efficiency • Quite low economic growth • Quite high energy demand
LG-HC	**JAZZ**	**SYMPHONY**	**GEI**

• Low government engagement • High international cooperation and integration • High liberalized context for business and trade • Brilliant world's economic perspectives • Policy concerns for CO_2 mitigation • Policy concerns for energy efficiency • High economic growth • High energy demand	• Energy equity • Achieving individual access and affordability of energy through economic growth • Improved technologies chosen in competitive markets • Energy sources compete on basis of price and availability • Growth of renewable and low-carbon energy • High economic growth • Low energy demand	• Environmental sustainability through internationally coordinated policies and practices • Polices on energy security • Governments pick technology winners • Governments subsidise and incentivise selected energy sources • Governments promotes certain types of renewable and low-carbon energy • Quite low economic growth • Very low energy demand	• Fossil energy replaced by clean energy • Growth of the share of electricity in end-use • Development of big renewable plant in Artic and equatorial regions • Development of an ubiquitous robust smart grid • High technology improvement • High economic growth • High cooperation mechanism

2.1.2 Comparison of the different scenarios on key indicators

2.1.2.1 Energy Intensity

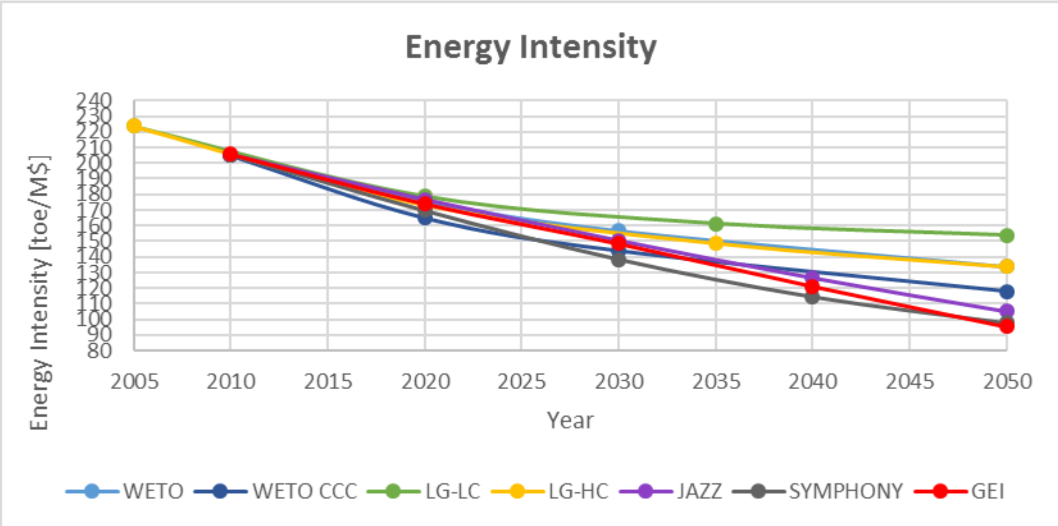


Figure 2 Energy Intensity in Tonnes of Oil Equivalent on Millions of US$ from 2005 to 2050[1]

In all the scenarios is forecasted a reduction of the energy intensity. The slightest decline is represented by LG-LC. It starts from 224 toe/M$ in 2005 and it decreases to 154 toe/M$ in 2050. WETO Baseline and LG-HC, instead, show very similar trend ending both to 134 toe/M$ in 2050. WETO CCC has the starting highest slope until 2020, assuming the lowest value in that year of 165 toe/M$, then the inclination decreases and energy intensity reach 118 toe/M$ in 2050. SYMPHONY, however, assumes the lower energy intensity values from 2026, being surpassed only by GEI scenario after 2047 and reaching 98 toe/M$ in 2050. JAZZ and GEI scenarios show, unlike the other cases where the trend is curvilinear, a linear behaviour. Both starting from about 205 toe/M$, they decrease linearly until 2050, in which JAZZ reach 105 toe/M$ while GEI occupy the lowest value of 95 toe/M$.

2.1.2.2 World's Final Electricity Consumption

The WETO scenarios and JAZZ and SYMPHONY scenarios have very similar trends. They start around 1.5 Gtoe and they reach a value around 4 Gtoe, except WETO Baseline which is few higher (4.2 Gtoe) and SYMPHONY which is a bit lower (3.7 Gtoe).

LG-LC and LG-HC with GEI scenarios, instead, represent the three higher trends. The highest is LG-HC, starting from 1.6 Gtoe in 2005 and ending to 6.6 Gtoe in 2050, a little less than the double of SYMPHONY in that year. LG-LC moves to 5.5 Gtoe in 2050 while GEI scenario stars with a slope similar to this last one, but after 2030 the inclination increases until reach the value of 6.3 Gtoe, that is more similar to the other scenario of the Energy Scenario Development Analysis - WEC Policy to 2050 (yellow line). The increase after 2030 goes hand in hand with the development of the global power grid and the increasing renewables electricity generation units, principally wind and solar.

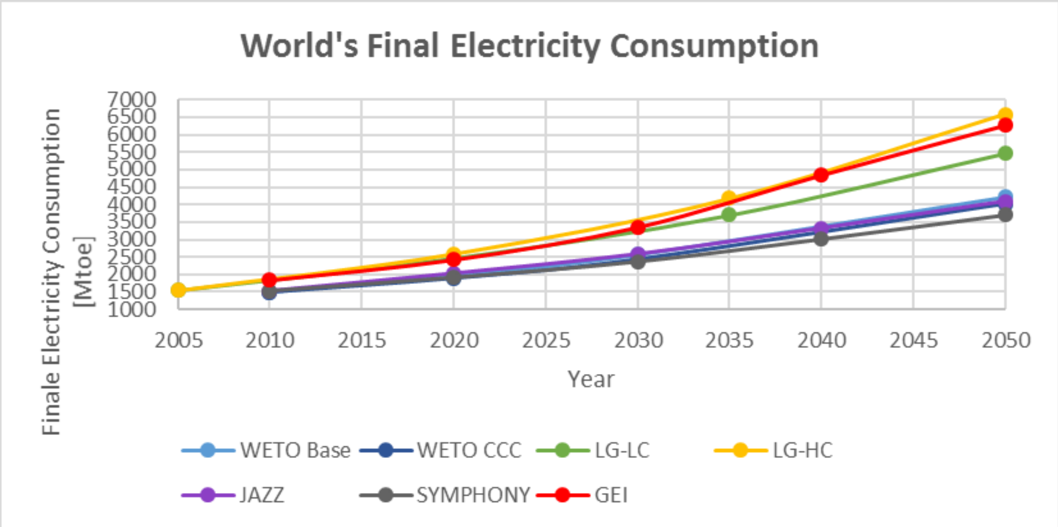


Figure 3 Final Electricity Consumption Worldwide in Tonnes of Oil Equivalent from 2005 to 2050[1]

Also electricity consumption does not follow the GDP trend. LG-LC present a medium-high consumption trend despite the GDP increase is the lowest. Contrarily, JAZZ scenario shows a quite low electricity end-use between 2010 and 2050 despite it forecast a very high economic rising.

2.1.2.3 Renewable Penetration

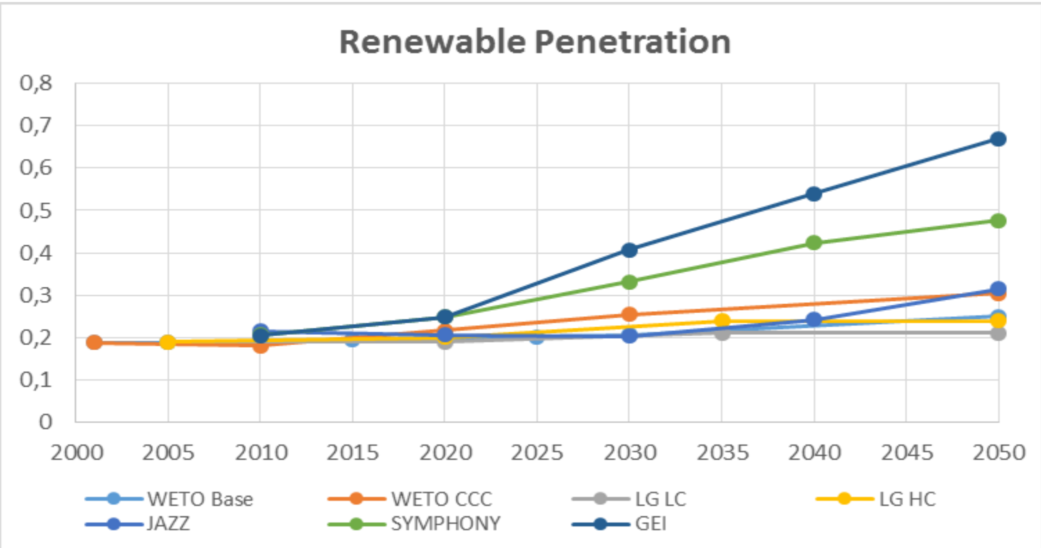


Figure 4: Renewable penetration trends

Renewable penetration in electric power systems (electricity produced by RES divided by the toal electricity production) trends will vary depending on the scenario considered. High renewables penetration rate both in medium and long term are forecasted only in the two scenarios where we have the highest level of political cooperation (Symphony) and the highest level of economic and investement strategy (GEI). In this case penetration can reach up to 66%. In all other cases RES penetration will slowly increase from around 0.19 to 0.25/0.30 in 2050.

2.2 EU energy perspective with focus on the electricity sectors

2.2.1 Policy Framework for the RES in EU

Even through the RES has a long history in power systems, it got large attentions of politicians and general public starting from July 2009 when the EU and the G8 announced an objective to reduce the greenhouse gas emissions by at least 80% compared with the 1990 levels by 2050. Following this objective, the European Council made the EU's objective to reduce the greenhouse gas emissions by up to 95% compared with 1990 level. After then, multiple EU's policies and directives set up a more and more clear path towards this objective.

Currently, the EU 2020 target is to reduce 20% of the greenhouse gas emissions on the level of 1990, to increase the share of RES to 20% in the total energy consumption and reach 20% increase in the energy efficiency [7]. The respective targets for 2030 are set to 40%, 27% and 27% [8].

Specifically, the EU countries are required to support the development of the RES such as wind, solar and biomass to reach the green energy targets. In 2013, the European Commission published the Green Paper to require an updated policy to design the energy system from 2020 to 2050. Followed by that, the Energy Roadmap 2050 and the European parliament resolution set a path towards a low carbon society.

In the European Strategic Energy Technology Plan (SET-Plan), the EU set up a technology road map up to 2020 [9], in which the following targets are set to raise the maturity of technologies and their market shares:

- Up to 20% electricity comes from wind power sources
- Up to 15% electricity comes from solar power sources and it will be even higher if the DESERTEC is achieved. The project aimed at creating a global renewable energy plan based on the concept of exploiting sustainable power from sites where renewable sources of energy are more abundant and transferring it through high-voltage direct current transmission to consumption centers. All kinds of renewable energy sources are envisioned, but the sun-rich deserts of the world play a special role.
- Electricity grid can integrate up to 35% of RES electricity
- At least 14% from bio-energy in the energy mix
- Nuclear still accounts for 30% of the EU electricity, the 4th generation nuclear reactors will be commercialized in 2040.

Even for the highest RES penetration scenario in the report of the 2013 technology map of the European Strategic energy technology Plan (Set-Plan), the conventional thermal power generation still has a notable percentage identified by the energy Roadmap 2050 [10], considering all possible technical transition and R&D supports.

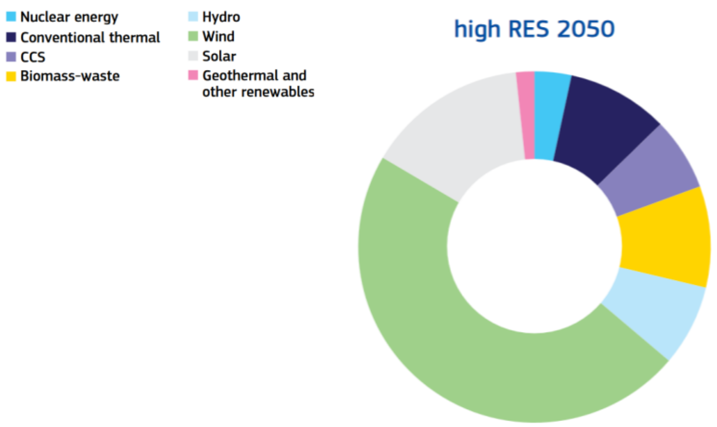


Figure 5 high RES scenarios in 2050 examined by the energy roadmap 2050 [11]

None of the current EU policies directly target 100% RES within 2050. However, in some researches and projects, several non-governmental bodies conducted scenarios for 100% RES by 2050, considering current policy frameworks.

2.2.2 EU reference scenarios

2.2.2.1 Background for the establishment of Reference Scenario

The commission conducted a market study on the energy supply and demand in the EU 28 member states. The conducted work also gave the future projections and scenarios based on various policy impacts.

The scenario started from 2010's EU energy systems under the assumption of present trends, including population and economic growth, policies both at the EU and the national levels, as well as the ones will be enforced in the future. It also considered high price volatile for energy imports, internal markets and technology deployments. The EU study aimed to give a path up to 2050. The scenario of 2020 was based on the achievement of the 20-20-20 Climate and Energy Package [12] and the Energy Efficiency Directive (Directive 2012/27/EU) [13].

2.2.2.2 General energy mix in the EU level in Reference Scenario

In the scenario derived by the EU reference Scenario, the trends of generation mix and installed capacity of the EU level are both derived as shown in Figure 6 and Figure 7 [14].

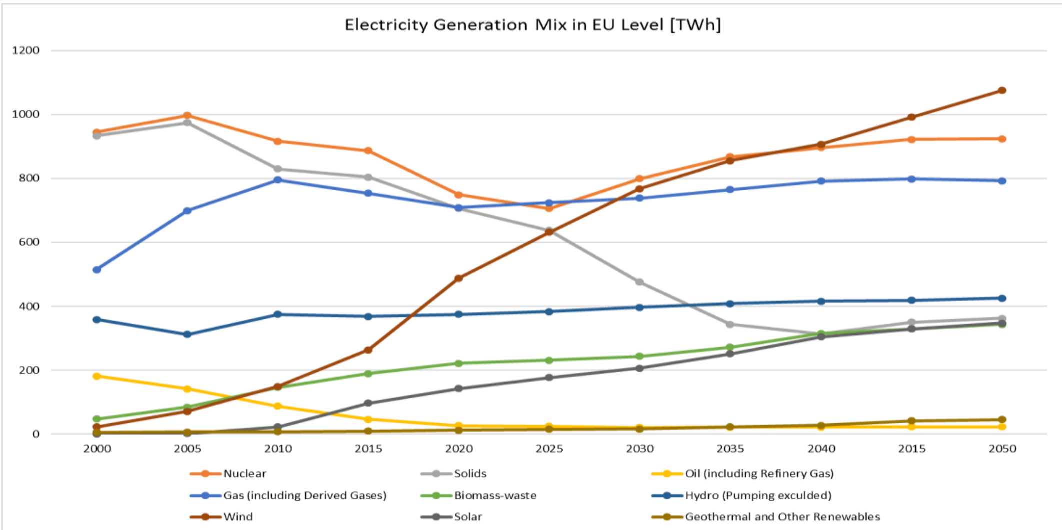


Figure 6 Trend for electricity production mix in the EU level

It can be clearly seen form the above picture that the wind power generation is increasing steadily until 2050, which has the same trend as solar and biomass power generations. While nuclear generation declines in the first stage until around 2025, then increased as the second power generation after wind. This is mainly due to the public attitudes on nuclear, policy formulation and the development of economics. Plus, the general consensus has been reached in many surveys that the lifetime of current power plants can be prolonged, which reduces the urgency for new established nuclear plants in a short term. Hydro, geothermal and other renewables seems very limited increases during this period. Although there is an increase during the first 10 years for gas power generation, a decline occurs in the next 10 years and finally recovering back to the same amount of 2010. The power generation based on solid fossil fuels declines from 2005 to 2040 until it has the same amount to biomass-waste generation. The oil power generation declines to a relatively low number with the least share in 2050.

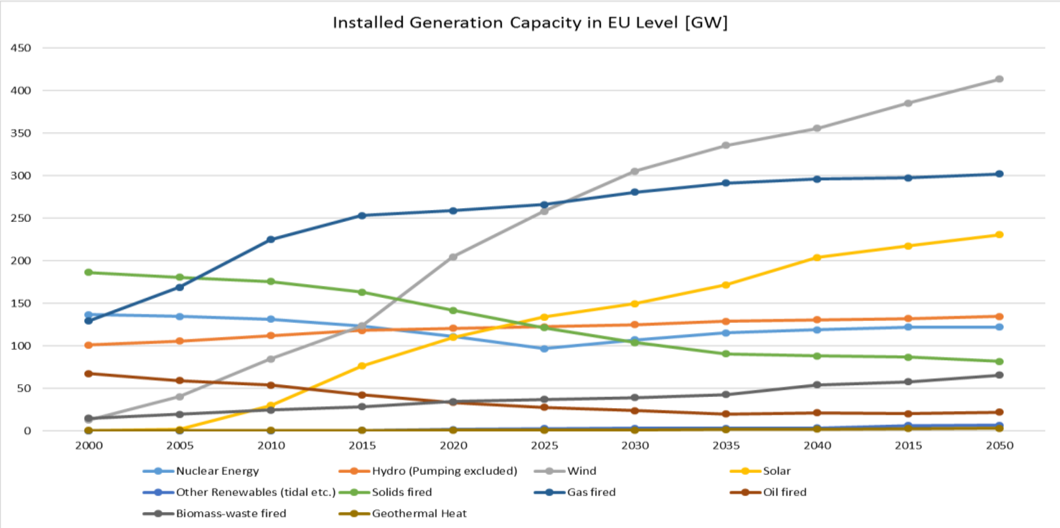


Figure 7 Trend for installed generation capacity at the EU level

With respect to the installed generation capacity, wind sees the largest growth of about 400GW over the 50 years, followed by the solar energy, and stands in the first place in 2050. As can be also concluded from Table 2, wind plays the major role in variable RES with the largest share in the whole period. The installed off-shore wind power plant accounts for about a quarter of total wind energy since 2020. The encouragement policy and the falling price of solar panels result in the improving share of solar energy in the future generation mix, which occupies the third place of installed capacity in 2050. Biomass-waste fired plant for power generation also sees a stable increase over time with a pretty low installed capacity at first. But in 2050, it is supposed to reach the same number of solids fired installed capacity in 2000, which means the biomass-waste fired energy will replace the position of traditional solids energy source. In 2050, the CCS devices are the basic equipment in solid-fired generation, which may further constrain the development of solids energy. Consistently with the trend of solids fuel power generation, the installed capacity of nuclear also has a valley in around 2015 and recovers back to the amount a little less than that in 2000 as the fourth in 2050. The initial downwards trend of nuclear reflects the nuclear phase-out policies adopted by EU MS (Germany and Belgium). Then, when the investments of new nuclear power plants exceed the expiration rate of the old ones, the installed nuclear capacities will rise. Hydro, geothermal heat and other renewables remain relatively stable during the 50 years with no more than 40 GW increase in total account.

The model of installed capacities for different energy sources are mainly based on the corresponding investments in each period. For the goal of reducing CO_2 emission, RES can easily get extensive attention and support from the public and the policy makers. Compared with other traditional fossil fuels, gas fired power plants emit relatively low amount of greenhouse gas. Although there is a quick increase of gas like the wind before 2015, the growth then slows down and the installed generation capacity is exceeded by the wind at around 2027. Moreover, the fast response of gas power plant can be regarded as a flexible regulator with large penetration of RES in the future power grid. Therefore, even the growth of installed capacity for gas slows down, the number is not going to decline in the entire period.

2.2.2.3 The trend for RES in the scenario

The most rapid increase of the renewable penetration happens before 2020, while it slows down afterwards due to the lack of new targets set by policies. Figure 8 summarizes the trends for the RES penetration of the EU reference scenarios up to 2050 according to [7] and [14]. The proportion of RES in power generation is supposed to achieve 35% until 2020 with an obvious increase of 15% from 2010. Plus, the RES is going to account for 43% and 50% of gross power generation in 2030 and 2050, respectively, in the RES penetration scenario.

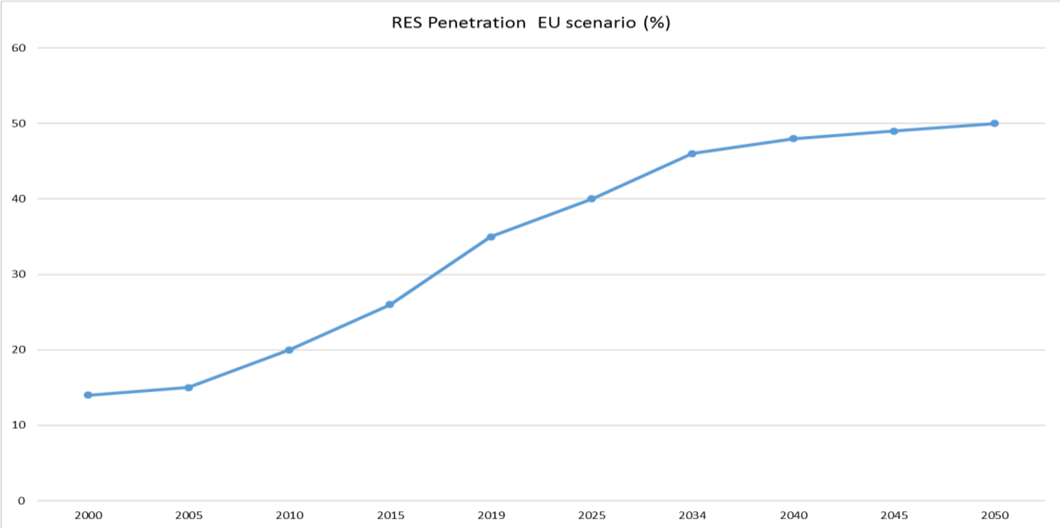


Figure 8 Trend for RES share in electricity production at the EU level

The improvements of energy efficiency are specially underlined in the scenario during the whole projection period, which is uncovered in the decoupled relationship between the GIC (gross inland consumption) and GDP growth. Besides, there will be a shift of the consumption mix among traditional fossil fuels and the RES. This is mainly due to the fact that innovative technologies and the mounting awareness of environmental protection encourage the increasing use of RES.

The implementation of RES policies to the horizon of 2020 and the growing ETS (Emission Trading Scheme) prices are the main factors determining the power generation developments in the reference scenario. However, with the increasing penetration of RES, it is necessary to establish adequate back-up capacity with high flexibility. Therefore, in the EU scenario, traditional power plants will still get investments at least up to 2020. Also, various policies of nuclear and CCS are taken into consideration in the scenario.

The transmission system of the electric power grid gets a large amount of funds in the scenario in case that the goal for an internal energy market is achieved and the plan of ENTSO-E for the 10-Year Network Development Plan (TYNDP) is completed. The success of a complex and comprehensive transmission system boosts the efficient use of RES considering the geographical distribution and declines the network electricity loss.

Advanced technologies for operation and control of electricity network enhances the stability of power grid and improves the possibility for larger penetration of RES. As shown in Figure 8, the percentage of RES is supposed to reach 35% in 2020, with an increase of 15% in 10 years from 2010. Although there are no specific policies for RES exploitation in the next 30 years when the scenario is to be made, it is believed that a stable increase will occur with a share of 43% in 2030 and 50% in 2050. This is due to the supposed encouragements from policies, Emission Trading System (ETS) prices, and the local public supports.

The intermittent RES mainly includes wind and solar as well as tide/wave, whose share are supposed to be steadily increasing as shown in Table 2: the growth of RES in Reference **Scenario**. In condition that the current exploitation of hydro energy is reaching its limit, the main contribution for the development of RES would be the variable RES.

Table 2: the growth of RES in Reference Scenario

year	2020		2030		2050	
	GW	%	GW	%	GW	%
Total RES	479	35	596	43	794	50
Intermittent RES	260	19	388	28	556	35
Wind	205	15	305	22	413	26
Solar	110	4	149	6	231	9

2.2.3 Studies on 100% RES in the EU

2.2.3.1 European Climate Foundation

In the report of the European Climate Foundation named “the roadmap 2050: A PRACTICAL GUIDE TO A PROSPEROUS, LOW-CARBON EU”, which fully respected the EU greenhouse gas emission targets. It included a scenario of 100% electricity generated from RES, considering mainly keeping an acceptable level of reliability. The study concluded that the reduction of at least 80% of greenhouse gas by 2050 is technically possible, which would require 95-100% of decarbonisation of the power sector, including RES, CCS and nuclear. However, with the target of 100% RES it recommended that for every 7-8 MW of wind or solar, one additional MW back-up capacity is needed [15]. In addition, 15% imports from North African and technology breakthrough, mainly on the enhanced geothermal, are required due to the reliability requirement. Besides, it also included the solar resources in the Middle East, and biomass imported from Russia and Ukraine.

By a back-casting approach, to achieve 100% RES in the EU in 2050, by 2020 the RES should reach 34% [15]. The identified generation mix is summarized in Table 3.

Table 3 Generation mix in percentage of production

Type	On-shore	Off-shore	PV	CSP	Biomass	Geothermal	Hydro	Import
(%)	15	15	19	5	12	7	12	15

As it is assumed 15% of the EU electricity needs to come from North Africa; therefore, it will also rely on an infrastructure enhancement to bring those energies into the EU through undersea HVDC cables.

2.2.3.2 E-Highway 2050 project

In the e-Highway2050 project, 5 long-term horizon scenarios have been identified to reach the decarbonisation objectives. Based on that, the major electricity highways have been studied to support the identified scenarios at the pan-European level from 2030 to 2050. Among the 5 scenarios, one is 100% RES, in which the wind generation accounts for 52% of the generation mix, whereas solar generation accounts for about 25% of the total generation mix [16]. The following Table 4 summarizes the 100% RES identified by this project.

Table 4 Generation mix of 100% RES scenario identified by e-hightway2050 in 2050

Type	Hydro	Wind	Solar	Biomass
Percentage (%)	21	52	24	9

At the EU level, the generation mix towards 100% RES identified by ENTSO-E (before 2030) [17] and e-highway2050 [18] are summarized in the following Table 5:

Table 5 Installed generation capacity in EU (GW)

Year	Wind	Solar	Biomass	Hydro	Nuclear	Fossil
2020	199.6	122	54	219.6	124	390
2030*	379	241	75	259	80	366
2040	544	466	129.5	336	40	150
2050	760	691	184	411	0	73

*Note: ENTSO-E TYNDP scenario EU green revolution

2.2.3.3 European Renewable Energy Council

Also, the European Renewable Energy Council conducted a research to investigate the contributions of the RES to the Final Energy Consumption in the hope to get the EU on 100% RES by 2050 [19]. In particular, electricity sector is targeted and forecast of a complete decarbonized sector is given within 2050.

Table 6 Contribution of Renewable Electricity Technologies to Electricity Consumption (TWh) [19]

Type	2007	2020	2030	2050
Wind	104	477	833	1552
Hydro	325	384	398	448
PV	5.4	180	556	1347
Biomass	102	250	292	496
Geothermal	5.8	31	169	601
CSP	0.8	43	141	385
Ocean	-	5	18	158
Total RES-E	543	1370	2407	4987
% Consumption	16	39.5-39.8	65-67	100-143

2.3 Irish and Romanian perspective

2.3.1 Romanian perspective

2.3.1.1 EU perspective on Romanian generation development

The generation mix of Romania is presently (December 2015) structured as follows:

Table 7 Current generation mix in Romania

No	Source of energy	P (gross values MW)	Percentage (%)
1	Fossil Fuels – Coal	6435.20	26.22
2	Fossil Fuels - Natural Gas	5561.80	22.66
3	Hydro power	6731.28	27.43
4	Wind Power	2979.79	12.14
5	Biomass	120.67	0.49
6	Solar Energy	1302.27	5.31
7	Geothermal Energy	0.050	0
8	Nuclear Energy	1413.00	5.76
9	Pump Storage	0	0
10	Distributed storage	0	0
	TOTAL	24544.08	100

On the other hand, according to the reference scenarios published in [14], the trend for electricity generation with different kinds of energy resources can be analyzed separately.

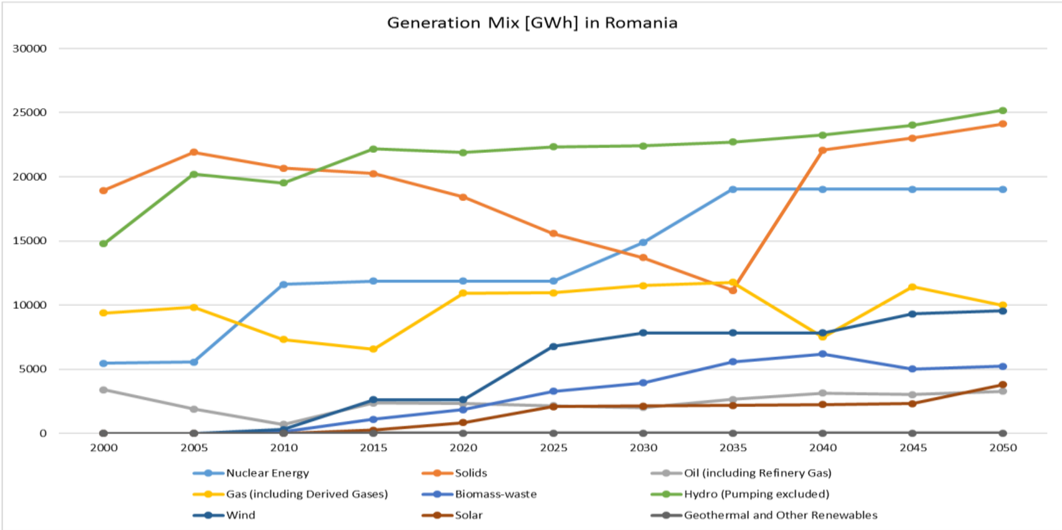


Figure 9 Trend for electricity production mix in Romania

Figure 9 illustrates the scenario of energy generation mix over 50 years in Romania. It can be easily seen that the hydro resource is adequate in this Country, which replaced the solid fuels as the largest source for power generation; they see a sharp decline since 2005, with the lowest number at around 2035. This comes with the high increase of nuclear power generation. The solid will finally rise back at the second place after hydro in the final stage. Taking the environment protection and investment into consideration, the value of nuclear electricity generation remains relatively stable since 2035. Considering the price impact, gas electricity generation only has limited fluctuations in the 50 years. Although variable RES including wind and solar energies keep increasing in the whole period, the total amount of them takes not much account in generation.

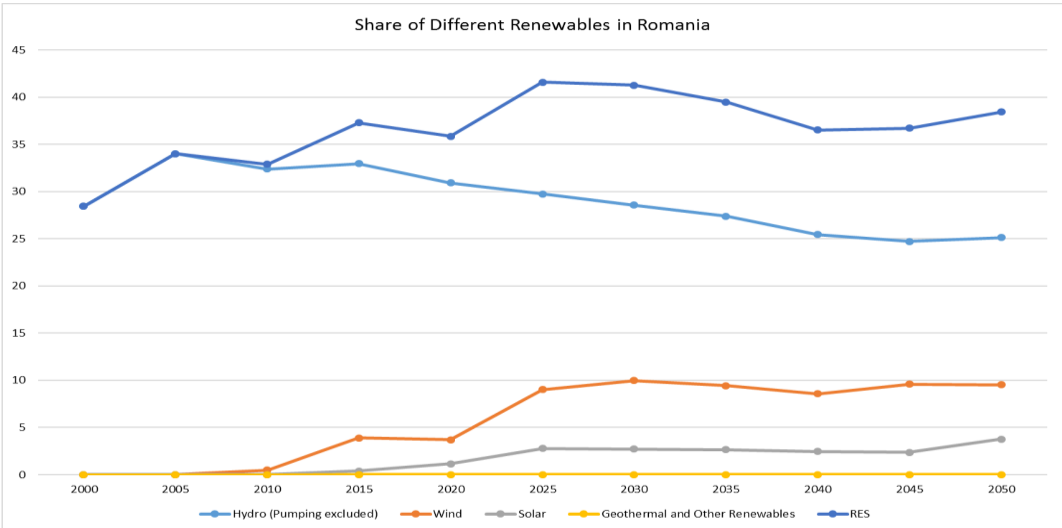


Figure 10 Electricity production share of renewables in Romania

A further analysis of the RES components can be seen in Figure 10. It reveals that among all the renewable energies, the hydro power plants play a dominant role while the shares of wind or solar are quite small.

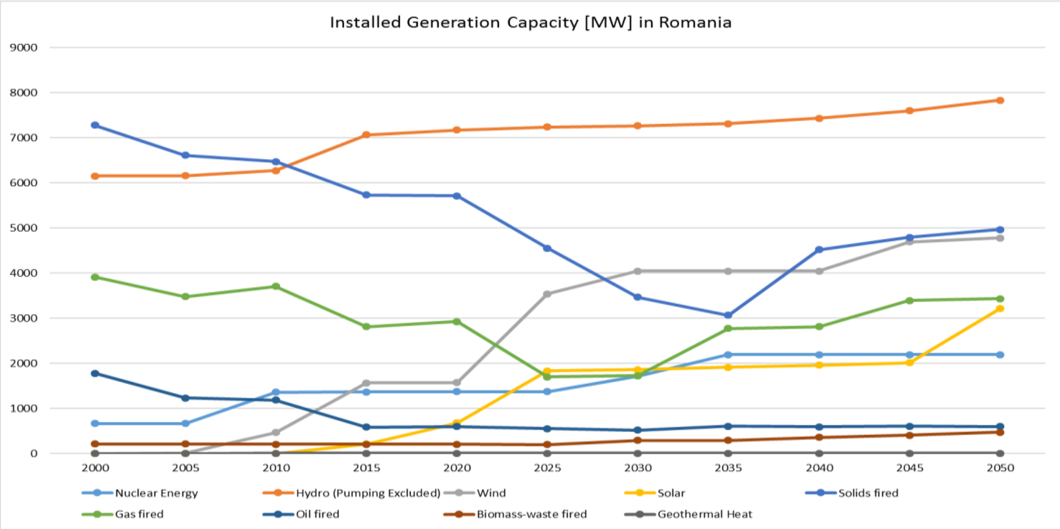


Figure 11 Trend for installed capacity share of renewables in Romania

In agreement with the generation mix, the installed capacity for each energy type is shown in Figure 11. For a higher exploitation of hydro energy resources, it is supposed to be a constant increase of hydro power plants over the 50 years. The solids installed capacity also encountered a valley at around 2035. Although the wind energy utilized for power generation is less than half of that of solids energy in Figure 10, the installed capacities of these two types of energy are almost the same, which partially results from the variable wind speed.

2.3.2 Irish perspective

2.3.2.1 EU perspective on Irish generation development.

Present and future scenarios are proposed in the following

- ***Present moment***

The generation mix of Ireland in 2014 [20] is structured as shown in Table 8:

Table 8 Share of different Energy sources for Generation in Ireland (2014)

No	Source of energy	Share in the whole Generation (%)
1	Fossil Fuels - Natural Gas	44
2	Wind Power	19
3	Fossil Fuels – Coal	15
4	Fossil Fuels - Peat	10
5	Net Import	8
6	Other Renewable	0.7
7	Waste	0.5
8	Fossil Fuels – Oil	0.1

The total Irish electricity generation from the report [20] in 2014 is 26 TWh. As presented above, the natural gas takes the largest part for electricity generation. Considering the coal and peat, traditional fossil fuel accounts for nearly 70% of total power generation. Although the proportion of traditional prime energy is pretty high, wind energy has taken 19% of the total generation as the second energy source. About 8% of the total electricity generation comes from import.

- ***Future Trend***

According to [14], we can extract the Irish renewable trend.

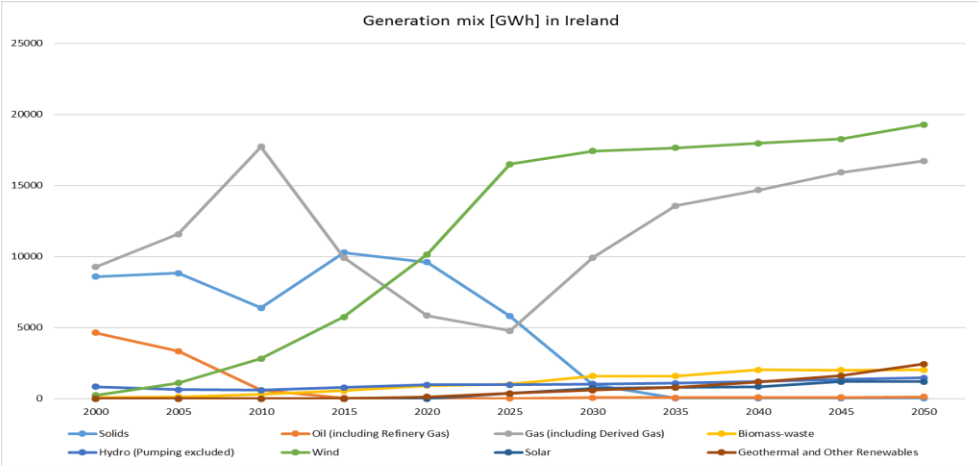


Figure 12 Trend for electricity production mix in Ireland

The most obvious characteristic in the generation mix of Ireland is that there is no nuclear power generation. Due to the lack of fossil fuels, gas and oil energies fluctuate roughly in the whole period. Wind power becomes the most important energy resource at the last stage. However, to cope with the random nature of increasing wind energy, the value of gas generation rises back after 2025 due to its flexibility.

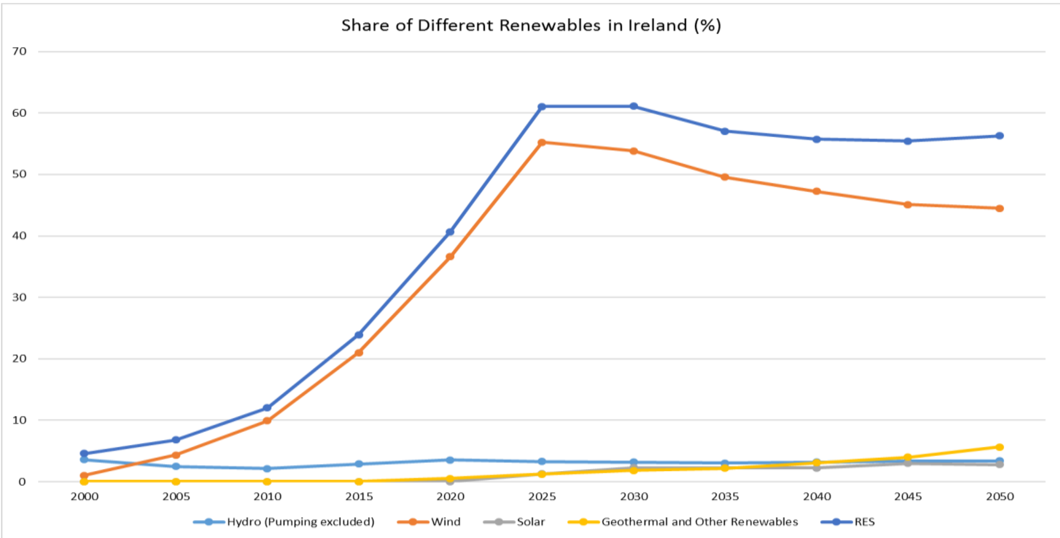


Figure 13 Electricity production share of renewables in Ireland

From Figure 13 it can be seen that the main contribution for the increase of RES in Ireland is the wind energy. The highly coincidence of wind energy and the total RES reveals the fact that rare renewables would be utilized in Ireland for power generation.

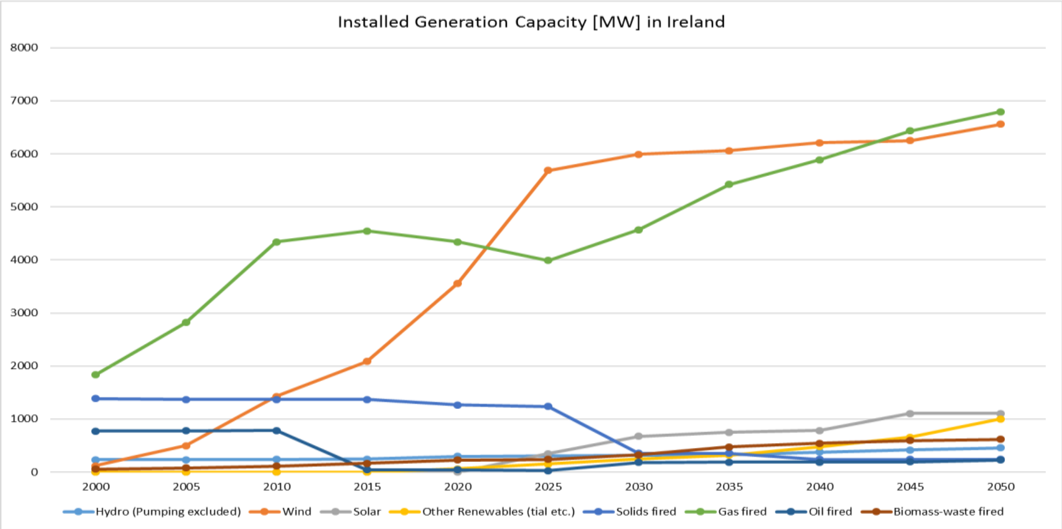


Figure 14 Trend for installed capacity share of renewables in Ireland

Figure 14 illustrates that the wind and gas installed capacities get stable increases over the 50 years, which is assumed to support the power supply in this island. Since wind energy is increasingly utilized, the solids installed capacity sees a sharp decline in 2025 and never rises back. Although the share of solar energy generation is relatively limited in previous analysis, its capacity also gets a stable rise in the 50 years.

2.3.2.2 100 % RES Scenario from other studies

The proposed scenarios for moving towards a "100%RES" is mainly based on reference [18] of the E-Highway project.

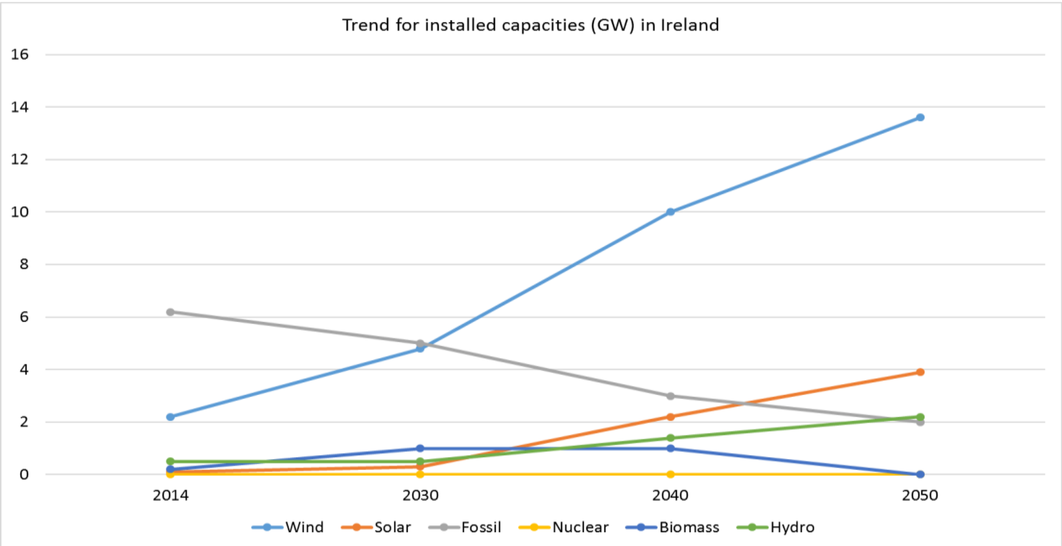


Figure 15 The trend of installed capacities (GW) in Ireland for a 100% RES roadmap

With a roadmap of 100% RES for power generation, the installed capacities of wind energy will have the largest increase in Ireland with a final value as 13.8 GW. Although solar energy is not well exploited at present, a sharp increase of its installed capacity is going to occur in 2030 and its value will exceed hydroelectric installed capacity two years after that. The installed capacity of fossil fuels will decline to about 2GW in 2050, a little less than the amount of hydroelectricity. The installed capacity of biomass will rise until 2030 and decline from 2040 with a stable value during these 10 years. In the final stage, the installed capacity of biomass would be very little.

One more should be mentioned is that, about 4.2% of total power generation have to be imported from abroad power grid in this 100% RES scenario.

3. Smart Function, Emerging roles and actors

High RES penetration grid introduced a change of paradigm in all the sectors composing the power system, from the generation domain to the utilization one. Due to the unpredictable nature of the RES, the correct operation of the system needs further components and functions, which we define here as “smart functions” because they can allow a more flexible operation of the system so that the secure transfer of electricity can be guaranteed. New actors are requested for providing these innovative services (such as management of distributed storage and local production by prosumers), as well as the changing the role of the “classical” actors of the system (e.g., the operators).

As the shift from the classical electrical network to a pan-European, smart and renewable-based electrical network is under way, there is no unique classification and definition both for the new functions that such system should be able to provide and the new roles needed. While the main Goal is to guarantee individually to the customers (both consumers and prosumers) electricity with a proper level of quality, new Smart Functions are emerging in electricity systems. Technological innovations and environmental constraints make future services, roles and actors of the grid still to be designed and understood.

3.1 Actors and emerging actors

For sake of clarity, this section provides a number of definition useful for understanding the different actors involved.

3.1.1 Actors of the electricity system

Distribution System Operators (DSOs)

The main objective of DSOs is to maintain the secure operation in DSs (Distribution Systems). Local voltage control is one of the tasks, which is now facing severe threat with the large penetration of RES. The intermittent and also unpredictable nature of RES also makes the power flow more complicated than in the past. Therefore, the DSO in future grid should act with more flexibility for the load flow equilibrium. DSO operations and task will also change due to the appearance of charging stations for electric vehicles. With smart meters, the DSOs are able to inform the consumers with detailed information of electricity prices and usage, which may have a positive impact on the cost and energy saving [26]. However, the present low reporting rate (hourly / daily) restricts the applicability of smart metering in network operation. Whether some functionalities of smart meters can serve DSOs in network current operation is still under discussion

Transmission System Operators (TSOs)

One main objective of TSOs is to keep the instantaneous power balance between the generation and consumption, including the active power exchange with adjacent power systems. They are also in charge of the secure operation of the system. The other main objective is to perform an efficient transmission of energy. There are also tasks including the development and maintenance of the grid, analysis of expected power flow and transmission of high-quality power electricity. The above list covers the role of the Transmission Operator.

However, when large amount of renewable energy penetrates into the power system, it is more challenging for TSO to use all available means (including power dispatching) for guaranteeing safe and secure operation of the Power System. A closer coordination and the exchange of information with DSO is needed to monitor the distribution grid, as this last is largely containing more and more generation facilities with unpredictable behavior. There are three possible ways for TSO’s operation [25]:

1) Continue to manage centrally only direct available ancillary services (balancing services);

2) Collect the aggregated balancing capacities and balancing energy connected in distribution system;
3) TSO and DSO fix separately the power flow in their own grid area.

TSO should implement robust grid codes to manage secure operation and deal with Supergrid transformation.

Regulator

The non-for-profit Council of European Energy Regulators (CEER) and the EU Agency for the Cooperation of Energy Regulators (ACER) are the executive bodies as energy regulator in Europe, which is responsible for the energy market and regulatory issues. The goal of the regulator is to provide a complementary approach to energy regulation and to unify the EU energy market to benefit all consumers. While with large penetration of RES into our grid, the problems regarding stakeholder investment and regulatory challenges in the development of smart grids need to be analyzed and settled by regulators [27].

Retailer

As TSO and DSO have very little commercial relationship with consumers, retailers are the ones who have the main commercial relationship with the end customers. They are also the first party to contact for the household customer regarding billing, house moves, switching requests and energy supply [28]. Their tasks include the understanding of customers' feedback as the last value adding party before energy is consumed. With the increasing share of RES, the power in customers' house will flow bi-directionally. The higher time-granularity of the information about the energy use of each customer is expected to be collected via the smart devices and further analyzed by the retailers.

Consumer

Communication in quasi-real time on wide arears, making potential answers to requests to modify electricity consumption becomes a feature of future smart grids. Consumers can benefit from this technology progress, which enables them to turn into a prosumer [30] or provide demand side response on the individual base.

Generation Units

Assembly of machines transforming any other energy source in electricity.

Dispatchable Units

Electricity generating units that can be scheduled on the wholesale market and whose output ranges between specific limits.

3.1.2 Emerging actors of the electricity system.

Non-dispatchable Units

Electricity generating units that which cannot be properly controlled, and hence cannot participate in the dispatching process

Prosumer

Prosumers are a kind of customers that not only can produce electricity primarily for their own use, but also provide the excess electricity to other customers. Their consumption can be optimized based on the market information. The excess electricity generated by themselves is able to feed back to the grid and benefit from it or to increase the rate of self-consumption thanks to the new emerging solutions of distributed/local energy storage. Innovative technologies make it possible for customers to buy and sell electricity at market price [29]. In addition, an increased rate of self-consumption is envisaged, based on emerging new solutions of distributed/local energy storage.

Load aggregator

Aggregators are new entities in the electricity market that act as mediators or brokers between users and the utility operator [31]. The present role of aggregators is to get the direct control of end-users' appliances with a pay to them. Therefore, once a peak-demand emergency occurs, they can shut down the energy-incentive appliances of the users for a short term.

EV station

As the trend of new technology, the emerging of electric vehicles will have a profound influence in the future power system. Within a smart grid, utilities can manage when and how EV charging occurs and apply specific rates for EV charging [32]. Although no business model has yet emerged for how utilities support EVs, there are three possible approaches including:

- Utility owns the EV station
- Utility subsidizes EV station
- EV station as an appliance

Virtual Power Plant (VPP)

In a smart grid with high penetration of distributed RES-based generation, it is possible to operate the small-scale generation units as they would emulate conventional power plants. The coordinating mechanism of VPP considers several factors, including the production facilities and the end users. The owners of the VPP can negotiate a much more favorable contract with electricity companies [33]. If the VPP only aims to participate at the energy market, it is defined commercial VPP, whereas it contributes to the system management is indicated as technical virtual power plant [34].

Balancing Responsible Parties (BRP)

License holder, which was recorded by TSO as Balancing Responsible Party under provisions of Commercial Code. A Balancing Responsible Party shall assume responsibility for others Licensed Parts. The Balancing Responsible Party is managing the group of defined grid users to stay within the schedule production/withdraw program. Its role is to manage as best as possible its internal balancing such that the BRP position is as close as possible to the scheduled program.

3.2 Key Smart Functions groups in emerging electricity systems

The electricity system is undergoing a deep shift both in its structure and in its operation. New function are already envisioned and ready to be implemented thanks to the wide spreading of ICT technologies into the grid.

Those functions are crucial for attaining the goals of sustainability, efficiency and affordability for electricity systems and play a major role in allowing a higher and higher penetration of RES.
With reference to this aspect, several synthesis have been proposed (e.g., [21] and [22]).

The evolution of the electricity system is basically involving all the domains that constitute the emerging electricity systems: generation, utilization, distribution and transmission. New functions are expected to emerge during the ongoing evolution. In the following, we list a possible set of high-level functions highlighting those one which can be considered more significant in RES penetration analysis. Any of these functions can be further divided in more basic and implementable functions.

- *Generation domain*

Grid support services by DER/RES: stand-alone DER (Distributed Energy Sources) or integrated prosumer systems will have to help the operation and the management of the grid by delivering grid services, for example providing synthetic inertia or enabling voltage control (for example, by introducing constraints on the percentage of power capacity which can be devoted to the grid services). Due to the big number and relative low capacity of DER plants, new techniques and regulations should be used to actual permit delivery of these services. Bigger plants in transmission grid will be instead easier to control.

Encouraging RES diversity: RES should reach more geographical uniformity throughout the system to avoid simultaneous, unidirectional variation of the production and therefore flexibility needs for the grid

- *Transmission domain*

Role of bulk energy storage: storage capacities (both in terms of high Power and Energy ratings) will be requested for secure operation of the grid in the short and long term, to allow the integration of high variable sources in the system even in the case of long period of limited supply. The need for longer-term energy storage can be called Bulk Energy Storage. Either the coupling with other sector (for example heat, transport, industrial interruptible processes) or by producing gas (e.g., hydrogen or methane) can provide this kind of long term storage

Supergrid: the transmission system needs to become smarter, by allowing higher flexibility for energy transfer while preserving stability. In fact, there will be a need of new lines (both HVAC and HVDC), due to both the foster interconnection between countries, and the link of RES to the grid. Various new techniques can be used to enhance capability of the existing infrastructure, minimizing the expansion of the transmission grid, which holds high costs, long time to build and low acceptance from local population. Some examples are:

Power flow control: to enhance the power transfer of the grid we can make use of phase shifters, interconnected HVDC lines and other power electronic devices (FACTS) which are able to control the power flow over lines. To optimize the use of these technologies there is a need of upgrading transmission system control and associated measurement technology.

Dynamic assessment of transmission capability: such an assessment is based on technology such as Dynamic Line Rating (DLR) [24]. Traditionally, transmission operators rely on static ratings for the capacity of transmission lines, which are normally conservatively determined based on “worst-case scenario” conditions. A demonstration project [24] confirmed the presence of real-time capacity above the static rating, in most instances, with up to 25% additional usable capacity made available for system operations.

Measurement infrastructure: reduced inertia in the system (due to an increased share of power converters mediated energy transfer), requires new control algorithms able to cope with smaller time constants (order of ms even in steady state conditions). This aim can be achieved with a measurement layer with high dynamic performances, and by implementing algorithms able to discriminate normal operation from fault conditions, by adapting the measurement set-up accordingly. Moreover, merging measurement data available with different reporting rates and/or embedding standard aggregation algorithms, will require an assessment of the quality of measurements as a function of on the physical model of the energy transfer in the considered grid section [44]. The availability of high reporting rate (up to 100 frames/s) synchronised measurements (for example phasor measurement units, micro-PMUs and advanced energy meters) is facilitating deployment of new control algorithms which are less sensitive to the limited knowledge of the overall system (line parameters, load curves, generation patterns etc.).

- *Distribution domain*

Active distribution grid: as the number of component continues to increase along with their higher complexity, secure operation of the grid will need new automated control system and two-way communication system to control distributed generation, consumption and storage and help stabilizing the grid. In this scenario, distribution networks will become “active”, i.e., allowing bidirectional power flows in normal operation. Distribution system can evolve to smart grids, which can make the global grid to become more resilient [23]. Smart grid is a framework which contains numerous functions, like real time metering and use of data, active role of DSO and more coordination with TSO for managing the grid etc.

- *Utilization domain*

Demand side management (prosumer's power profile control): Prosumers will be able to control into a certain extent their power withdrawal/injection profile. This capability will make the prosumers responsive to external signals (price and technical), providing services to the grid in terms of power/energy balancing, voltage profile regulation, backup power, etc. In this framework, the prosumers can accommodate DER that will represent the "active" part of the prosumers providing local generation capability. The impact of DER at this level will be two-folded: from one side it will allow higher penetration of renewables as a whole, whereas on the other hand it will guarantee to the prosumer the possibility of self-generation and power injection into the grid.

Role of distributed storage at DS and prosumer level. Based on latest advancements in storage technologies, it is expected a progressive penetration of distributed storage in the period 2020 – 2025. This will serve both DS and prosumers for auto-consumption of their produced energy (as feed-in tariffs become less attractive than using the energy locally)

- *Inter-domain*

- **Market liberalization and transformation:** Market will progressively give more values in gathering of flexibility resources more than bulk energy production for itself, as variable cost of production of RES are substantially zero. New players will enter this flexibility to enhance its low-cost service and, for the same reason, transaction will happen almost in real time with shorter dispatching period (up to ten minutes, where RES forecast are more robust). Average variability of RES and finding of flexibility resources can be achieved by unification of European markets and networks by more interconnected power systems. Finally, Market rules and incentives should be implemented to make the consumer and generation units to behave in an optimized way.

4. Introduction to technical issues for RES penetration

In this chapter, first of all, we define in a rigorous way what stability is in a power system. Then, the problem of why power system needs inertia or synthetic inertia is addressed. After that, we briefly discuss the frequency issues in the system, and then voltage issues, which are the main dynamical problems of the grid (highlighting the RES influence and possible new methods and strategies to deal with the future generation mix of the power system, which will be extensively studied during RE-SERVE project).

4.1 Stability definition

Many definitions and classification to define stability in a power system were used during the years. Definition should have a consistent and general mathematical underpinning description but, at the same time, it has to have a clear and physical motivated meaning.

Last attempt to define and categorize power system different stabilities was done in 2004 [36]. The proposed definition for the general power system stability is:

"Power System Stability is the ability of an electric system, for a given initial operating condition, to regain a state of operating equilibrium after being subject to a physical disturbance, with most system variables bounded so that practically the entire system remain intact"

Power system is a highly nonlinear system that operates in a constantly changing environment. Disturbances can be of various nature and various intensity, like load stochastic changes or short circuit or big generator trips.

Due to its complexity, it is the norm to make simplifying assumption and isolated more specific kind of instabilities based on (i) consideration on physical nature of the instabilities and main system variable involved, (ii) size of the disturbance and (iii) time span that must be taken into consideration

Figure 16 shows the power system stability categories.

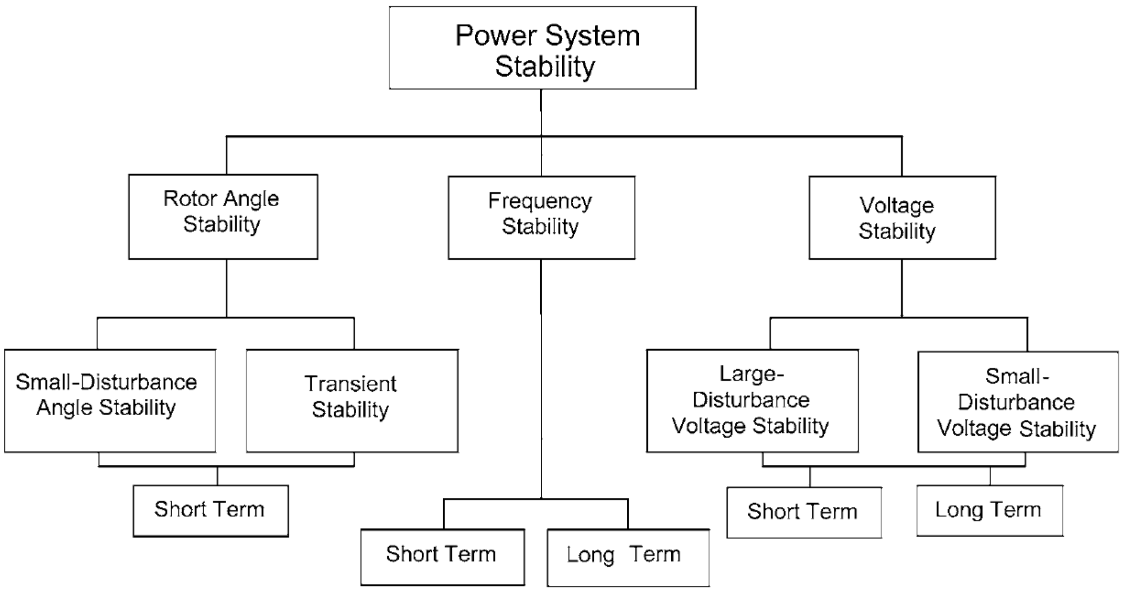


Figure 16: Classification of power System Stability [36]

In particular, we have:

- Frequency stability

Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. Instability occurs in case of big contingencies in the form of sustained frequency swings leading to the tripping of generating units.

Frequency stability may be studied in *short term* corresponding to the characteristic time response of devices such as under frequency load shedding and generators control and protection, or in *long term* corresponding to the response of prime mover energy supply systems and load voltage regulator.

- Voltage stability

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. The main driving force usually resides in the increment of reactive power flow from the loads, which cannot be sustained by generators without decreasing voltage level at the corresponding buses.

Voltage stability may be studied in case of *large disturbance* referring to the ability to sustain large disturbance such as system faults, loss of generation, or circuit contingencies or in case of of *small disturbance,* due to small perturbations such as incremental load change in the system load. Both kinds can be regarded as short term or long term phenomena depending on processes and components involved.

4.2 Inertia and synthetic inertia

Inertia is a kind of resistance, which all physical objects have, to the change of their motion state when an equilibrium has been broken. Similarly, in power systems the following three items define the system dynamic behavior when it is not in equilibrium:

1) *mechanic power* P_m fed into synchronous generators, created by primary resources (such as gas, carbon, hydro, etc.)
2) *electric power* P_e fed into the electrical grid, which is generated by synchronous generators
3) kinetic power stored in the rotating masses of the generators, which is related to the *inertia M* of the generators. The relationship among them can be expressed as:

$$P_m - P_e - M\frac{df}{dt} = 0 \tag{1}$$

where f is the system frequency. When the system is in an equilibrium point, the system frequency is equal to its nominal value f_0, e.g. f_0=50Hz in Europe, and the differentiation of frequency is equal to 0.

Under normal operation of the system it is assumed that frequency is a system variable, known with an error less than 1%, which is the same in all nodes of a synchronous system (steady-state approach). However, high-resolution synchronous measurements reveal that frequency deviates in space, and the magnitude of deviation depends on the system infrastructure (including availability of inertia) and meshing of the lines. Usually the synchronous generators of the system operates in synchronism between them and therefore these differences are very small. Moreover, frequency definition and measurement framework are referring to the PQ definitions (IEC61000-4-30 ed. 2015), i.e., as an arithmetic average over an observation window of 200ms (in 50 Hz systems).

We will use the term *RoCOF* (Rate of Change of Frequency) for the frequency derivative, although presently there is no IEC definition for this quantity. The observation is particular important when standard frequency aggregation algorithms are considered/applied [45].

However, when the equilibrium has been broken (e.g., P_e suddenly changed while P_m is unchanged), the frequency will change according to equation (1). Therefore, the *RoCOF* is dependent on the inertia *M*.

The higher *M* is, the slower the frequency change will be. In other words, the lower the rotating mass is, the more delicate the system equilibrium would be. Therefore, the existence of inertia eventually prevents a sudden change in system frequency.

However, with increasing amounts of wind turbines (small inertia) and solar panels (no inertia) connected to the grid, the system is facing a severe threat due to the decrease of traditional mechanical inertia. The appearance of full-power converters in power plants even aggravates this situation, due to the decoupling during the conversion of energy from DC to AC. The lack of inertia then may cause frequency stability problems in the power grids as the RoCOF can become very high and existing control systems do not consider reduced time constants in the control loop yet. Also, normal measurement set-up (with lower reporting rates, i.e. high filtering properties of the original frequency information) is not adequate to provide the control algorithms information with high bandwidth.

Synthetic inertia is proposed to emulate the exchange of rotational energy that exists in synchronous machines within the power system. A virtual inertia can be obtained with power *electronic converters* and a proper *control strategy* to absorb or discharge power from the *energy storages* (Figure 2). The unit will then behave like a synchronous generator from the grid point of view, which realizes the damping properties of renewable energy sources and enhances the frequency stability of the system. The power electronic converter with such concept plus the energy generation and/or the battery technologies is commonly referred to as virtual synchronous generator (VSG) [34].

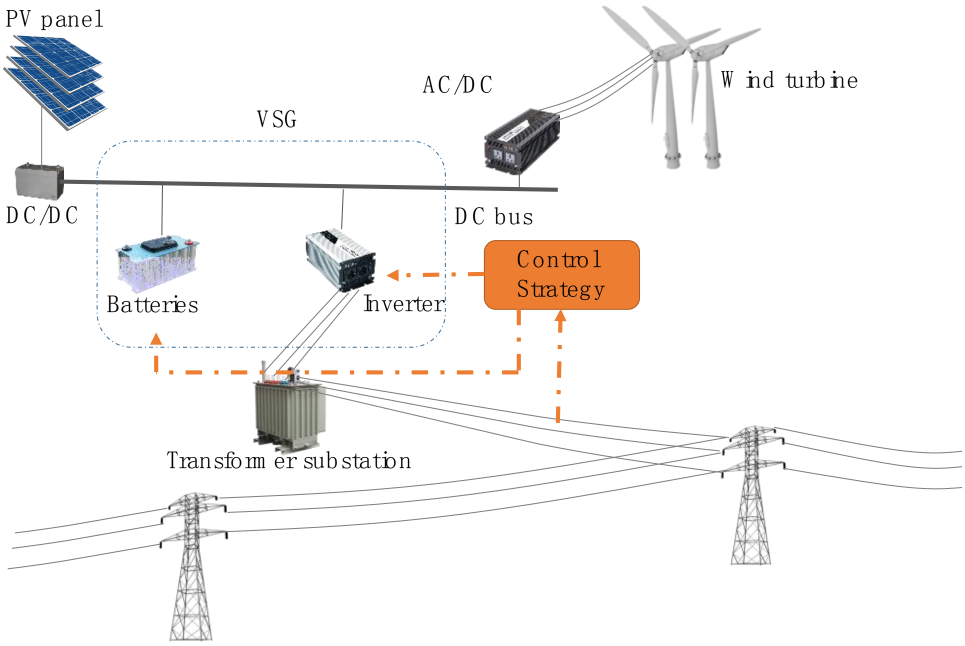


Figure 17 General structure and concept of the VSG

The structure of the VSG normally consists of energy storage and an inverter equipped with a specific strategy. It mimics the inertia and damping property of synchronous generators for renewable energy sources to deliver power from them to the power grid via the inverter connected between DC bus/source/distributed generator and the grid. Since the frequency problem is essentially caused by the imbalance of active power, the synthetic inertia will be realized by controlling the active power inversely proportion to the frequency deviation.

In the steady state operation of power systems, power generation and consumption are balanced and, therefore, the frequency remains constant. Once the load or generation changes, the energy stored in storage should instantaneously balance the demand, and generation with the concept of VSG by emulating the effect of inertia, as presented in the VSYNC FP6 project [46][47].

4.3 Frequency issues and control

4.3.1 Frequency stability aspects

Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant unbalance between generation and load [36]. Frequency of a grid can be considered to be unique, even if in reality are present small differences between generators (under non steady state conditions). However, this applies exactly only in the case of synchronization of the grid synchronous generators, or under the hypothesis of rotor angle stability. Actually, converter RES generation influences modes of oscillation of the system, and even if no convergent result is evident [37], it is necessary to pay attention to synchronization issues.

Any frequency deviation implies a corresponding grid angular frequency deviation, since the relation $\omega=2\pi f$. Because the system frequency and the angular frequency are global quantities, any unbalance between generation and load affects the operation of all synchronous machines of the power system. Any change in the angular frequency results in change in the electromagnetic torque and finally unbalance between the electromagnetic torque and the mechanical torque of each synchronous machine. The change in the angular frequency is given by $\Delta\omega= \Delta P/H_{sys}$, where ΔP is the active power unbalance and H_{sys} is the system inertia calculated as the sum of inertias of all turbine generators (moving parts) in the power system. Inertia of a turbine generator refers to the turbine generator resistance to changes in the rotor speed. With the increased penetration of RES, the power system inertia can decrease and, as remarked previously, the frequency can show important sudden variations, which call the implementation of VGSs. Nowadays, ENTSO-E monitors the European situation trying to find minimum and suggested values for inertia in the grid to avoid load shedding or other emergency situations [38]. As inertia goes down national TSO are obliged to increase the capacity reserve for the grid (primary, secondary and spinning reserve) increasing the costs of managing the grid (paid by all the consumers).

Large frequency deviations are due to the inability of the energy sources to maintain/restore balance between system generation and load. The instability, that may result, occurs in the form of sustained frequency swings leading to tripping of generating units and/or loads. For this reason, timely and optimal actions must be taken in order to minimize the amount of interrupted load [39].

The characteristic time of the processes evolving during frequency excursions can range from few seconds (corresponding to the responses from the generator control and protection devices and the under-frequency load shedding protection), to several minutes (characteristic to the prime mover reaction time or load voltage regulators) [36]. However, the time characteristic for triggering the frequency instability depends on the power system size. Therefore, the power system frequency stability can be either a *mid-term* phenomenon or a *long-term* phenomenon. Mid-term frequency instability and collapse can be observed in islands created after network splitting with insufficient generation resources and inappropriate control equipment [40], while long-term frequency stability problems, potentially leading to system collapse, can be observed when the steam turbine over-speed controls or boiler/reactor protection and controls do not properly operate [41][42].

4.3.2 Current architecture for frequency control in Europe

The power systems are designed with automatic and manual control systems that are used for the load-frequency control. In Europe, the frequency control is performed on three levels. The primary (frequency containment) and the secondary (automatic frequency restoration) controls are automatic systems and are able to respond very quickly to frequency deviations. The third control level consists in manual deployment of power reserves upon the call of the dispatching centre; it is divided into the fast-tertiary (manual frequency restoration) and slow-tertiary (reserve replacement).

The primary control is designed to stabilize the frequency in the first seconds after perturbation occurrence, whereas the secondary control is designed to automatically balance the generation and load and bring out the system frequency within predefined limits. The secondary control level is performed by the Automatic Generation Control function implemented in the EMS/SCADA system. The third control level has the purpose to replace the secondary reserve so that sufficient automatic active power reserve is maintained in the system in order to counteract inadvertent power unbalances and frequency and/or active power exchange deviations [39].

Figure 18 shows the ENTSO-E standards and dynamics for frequency control.

The national grid codes require that appropriate power reserve be available in the power system for both upward and downward regulation in order to face the inadvertent loss of generation, according to [43]. The neighbouring power systems can contribute to restoring the balance between generation and load. However, danger may also come from faults that can affect the network integrity.

The hydro-generators may run almost unaffected when large drops in frequency occurs, even up to ten percent. Conversely, thermal power plants are very sensitive to frequency drops, even by five percent. Since the PV power plants and PMSG wind generators are connected to the electrical network via a power electronic based converter, they can better adapt to frequency variations. However, induction generators can be severely affected by large frequency variations.

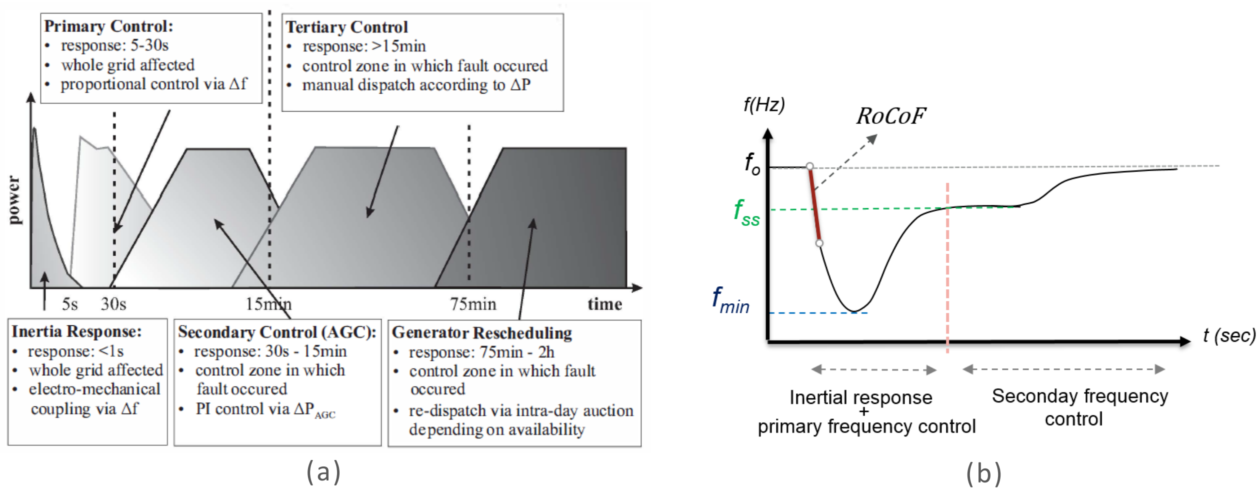


Figure 18 a) ENTSO-E frequency control categories [36] b) Frequency dynamic response

4.3.3 Proposed strategies for RES integration

RES may experience fast variations in the generated power during a dispatchable interval (one hour in Romania) as a result of the fast changes in the availability of the primary resource. In countries like Romania, the wind speed is characterized by gusts and wind speed variations, while sudden clouds may affect the generation from PV. An example of wind generation in Romania is shown in **Figure 19** on November 13th, 2016, when wind generation is fluctuating between 800 MW and 2500 MW. The power exchange with the neighbouring systems is shown in red line.

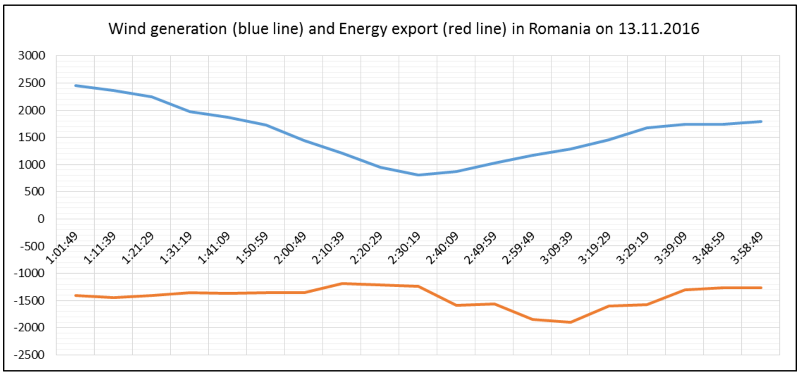


Figure 19 Wind generation and energy export during 4 hours on 13.11.2016 in the Romanian power system [49].

In Romania, most of the PV plants and a large number of wind generators are connected to the distribution networks. The small units (installed power less than 5 MW) are not controllable (i.e., non-dispatchable), which means that they are not included in any level of the frequency control system. It is expected that there will be a massive deployment of PV panels in the MV and LV networks within the next 10 years. The larger will be the number of small RES units, the more difficult will be to provide the active power balancing control.

The increase of energy generation from RES toward the 100% target may require some technical and administrative changes, such as:

- Massive deployment of energy storage systems: electrochemical batteries, flywheels, compressed air based systems, etc.;
- Development of both pumped storage power plants and classical hydro power plants[1];
- Redesigning the secondary frequency control: a) defining more levels in terms of the deployment time, with setting intervals spanning from less than 2 minutes to 15 minutes; b) changing the calculation procedure of the available secondary reserve band for the generation units. Adaptation of the central frequency regulator for level deployment of secondary reserve may be required.
- Analysis and redesign of primary frequency control strategy in conjunction with secondary frequency control, in different aspects such as the concepts regarding time for restoring the primary reserve and the dead-bands of primary frequency control, in order to have wide-spread but also cost-effective solutions.
- Finding the appropriate and cost effective solutions for increasing the synthetic inertia and connection with primary frequency control solutions, especially when they are both relying on local storage resources.
- Changing the European legislation in what regards the ownership of main power plants used for frequency control. In Romania, for instance, the largest contribution of frequency control comes from hydro generators. The HH Index[2] is about 4200 for the secondary reserve, 5000 for the fast-tertiary reserve, and 5500 for the slow tertiary reserve [50]. The seasonal storage plants could be exclusively used for power balancing.
- Coordinated control of groups of generation sources through the *virtual power plant* concept.
- Implementation of dynamic energy trading, i.e. flexible inter-hour trading.
- Participation of wind power plants and photovoltaic power plants into all levels of the frequency control system[3].
- Large implementation of demand response: promoting the *smart house/building* concept; control of EV charging as a response to frequency control; implementation of intelligent control of street lighting, etc.
- Improve the prosumer's role and its local network architecture, by becoming a complex entity with flexible consumption, production and storage means, facilitated by hybrid (AC and DC) local networks.
- Improve neighbourhood energy exchange, associated markets of energy and energy services and encourage micro grids AC and DC solutions, in order to increase local resilience and to mitigate/reduce renewables drawbacks on higher levels of the grid through a hierarchical control and optimisation.

[1] Note that, diversification of the storage systems is a sine-qua-non-requirement, taking into account the need for long term – days – energy storage

[2] The term "HHI" means the Herfindahl–Hirschman Index, a commonly accepted measure of market concentration. The HHI is calculated by squaring the market share of each firm competing in the market and then summing the resulting numbers [48]

[3] Note that, under the actual situation of capital costs for renewable energy sources, large deviations from the optimal generation will result in loss of energy use and thus loss in energy trade

- Establish appropriate and standardized methodologies for measuring frequency and *RoCOF* in the situation of system transient situations (i.e., non-steady-state), to be implemented at all levels of protection and control.
- New algorithms and hardware equipment for processing the frequency measurement data. Intermittent generation from RES results in fast frequency variations, which have to be correctly identified.
- Implementing HVDC links/networks across countries for sharing the resources for power balancing, besides energy trading.

In the frame of RESERVE, the concept of *linear swing dynamics* will be developed, exploiting the significant reduction/elimination of SGs with their electromechanical oscillation and the high deployment of fully controlled power electronics. Based on that, novel frequency control concepts will be developed for DC systems, RES, storages and rotating mass-based loads. The control strategies are inspired from the so called *Virtual Inertia* (VI) and *Synchronverters* [51], [52]. The objective is to provide virtual-synthetic inertia and achieve systematic enhancement in frequency stability.

4.4 Voltage issues

4.4.1 Voltage stability aspects

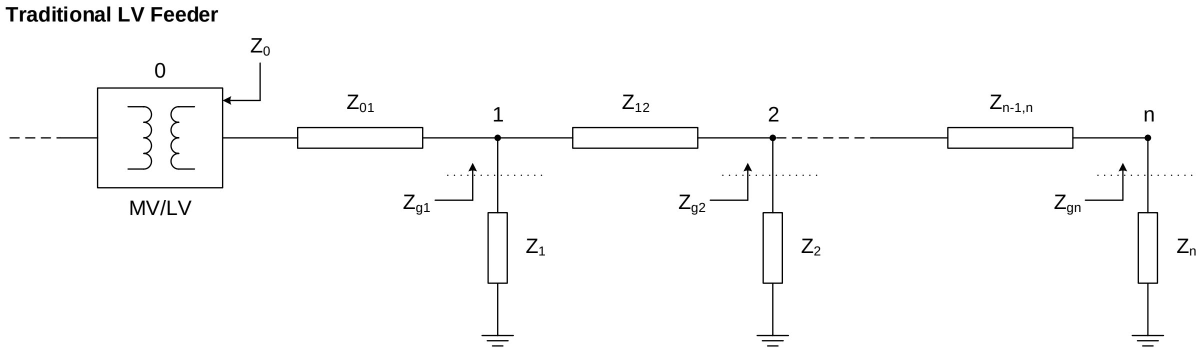
In the following we will use as voltage value the rms value aggregated (according to IEC 61000-4-30) over 200 ms or 3s. Measurement equipment are using – all – this definition. SCADA information however does not provide a clear algorithm (analogue filtering + aggregation algorithm on the digital filtering within the IED units) for computing the rms value of voltage. This is of high importance when coordinating protection settings following the numerical simulation results.

Voltage values in the grid should stay within acceptable limit in all the operations of the grid, to avoid disturbances in electrical components and correct transmission of energy. The goal is to keep voltage drops as small as possible (flat voltage profile). Due to the strong coupling between reactive power and voltage levels, in general, an increase of production of reactive power results in higher voltage near the production source, while an increase of consumption of reactive power results in lower voltage. Moreover reactive power cannot be transported over long distance due to the inductive nature of the lines (especially transmission lines). Reactive power is considered a local quantity and there exists in the grid a lot of “consumers” of reactive power and a lot of “producers” (like generators, capacitors, FACT devices etc.). In distribution systems with radial configuration, voltage profile is expected to drop continuously along the lines.

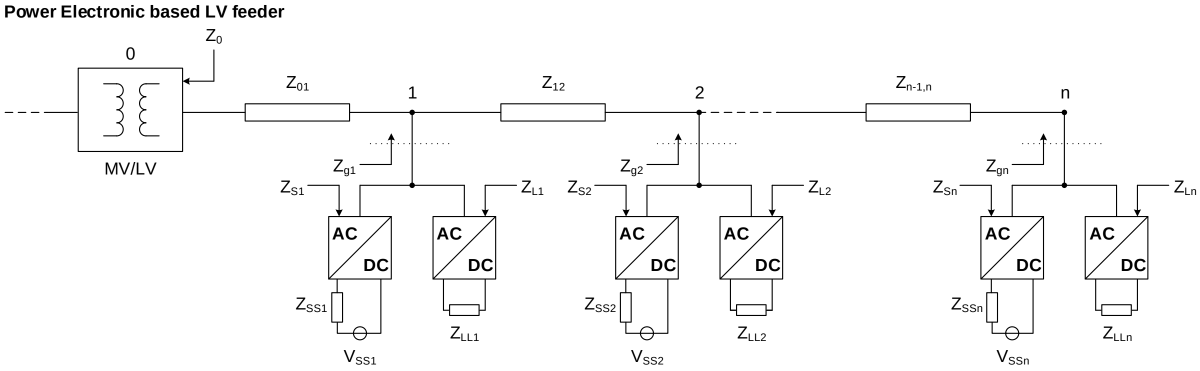
The cause for voltage instabilities is the load active and reactive energy transfer. Moreover in the case of reactive power, to keep adequate voltage level the reactive power should be produced as near as possible to avoid transportation of reactive energy.

Voltage instabilities or collapses are caused by sudden load increase, load recovery after faults, reactive losses due to high power transfer, loss of local reactive supply [53]

For what concern renewables sources, by focusing on distribution level (i.e., MV and LV, where it is expected to reach faster the “up to 100% penetration of RES”), the transformation of AC Power Distribution Systems is illustrated in Figure 20, representing an exemplary LV radial feeder. In Figure 20a, the traditional AC LV feeder is mainly a passive network because the majority of loads are either AC machines, resistive, or diode rectifiers, fed by the MV/LV transformer. In Figure 20b, the counterpart Power Electronics AC LV feeder is an active network, where inverters interface the distributed RESs, and active rectifiers interface all the loads.



(a)



(b)

Figure 20 (a) Exemplary traditional passive LV radial feeder
(b) Counterpart power electronics based feeder

The only voltage problems faced on the traditional passive LV feeder in normal operation were related to the connection/disconnection of significantly large loads. These load changes create under- and over-voltage problems on the voltage profile along the feeder. To solve these issues, the On-load Tap Changer (OLTC) transformers located at substation level were the only voltage controllable units able to compensate for such voltage problems.

The new scenario, i.e. the Power-Electronics-based AC Power Distribution System, is depicted in Figure 22. Due to the deeper penetration of RESs and loads through grid-connected power electronic converters, the traditional AC Power System is transforming into a Power-Electronics-based AC Power System. As power electronics penetrate the AC grid, a challenge related to small-signal voltage stability and control is presented for power electronic engineers, power systems engineers, and ICT experts. It is known that this proliferation of grid-connected power electronics can have a destabilizing effect on the AC voltage due to interactions between feedback-controlled grid-connected power electronic converters and equivalent power grid impedances seen at the various Point of Common Couplings (PCCs) [54].

4.4.2 Current architecture for Voltage Stability

In normal architecture, we may distinguish 2 or 3 hierarchical level of Voltage Control.
Usually the task of the primary voltage control is to control the reactive output from a device so that the voltage magnitude is kept at (or close to) the set value of the controller when local disturbance (load and generation profiles) changes voltage values. The selection of the set of values is the task of the secondary voltage control [55]. In the following, we propose a collection of basic definition useful for getting insights regarding the voltage control.

Primary Voltage Control: a series of local system intervention which try to restore locally some voltage level set points.

- **Automatic Voltage Regulator:** It is a regulation implemented by synchronous generator in an automatic way by controlling excitation current to stabilize local node Voltage level to a certain value.

- **Reactive Shunt Devices:** Shunt capacitors and reactors banks are used for a coarse control of reactive power by manually or automatic discrete activation.
- **Transformer Tap Changer:** An important method for controlling the voltage in power systems is by changing the turns ratio of transformers and therefore keeping voltage values from the other side at acceptable levels for example in distribution networks, where the voltage at the consumer side can therefore be kept fairly constant even though voltage variations occur on the high-voltage network.
- **FACTS Controllers:** power electronics-based equipment such as Static Var Compensator (SVC) and STATIC synchronous COMpensator (STATCOM) which can achieve a fast and more powerful control.

Secondary Voltage Control: Local control alone can end up with uneven distribution of reactive power over generators and voltage profiles across the line. By controlling the Voltage levels of some specific pilot nodes, the Secondary Control will send a signal to specific generators, which will be adjusted by a local reactive regulator taking in consideration of generators capability, and then will delivered as supplementary input to the AVR.

Tertiary Voltage Control: Choosing of optimal pilot node values or Voltage profile can be done manually or periodically or online during operation by using particular methods like ORPF (Optimal Reactive Power Flow), which tries to minimize power losses in the system taking in consideration security voltage constraints. The computation needs data of load, generation and transmission conditions to optimize pilot nodes values. Hierarchy is illustrated in its basic structure in **Figure 21**.

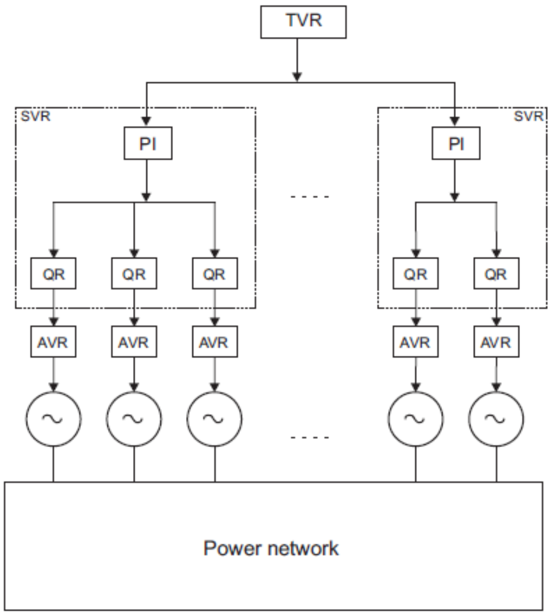


Figure 21: Structure of the Voltage regulation

4.4.3 Proposed Strategies for RES Integration

With the advent of RESs connected to the grid with power electronic converters, new controllable units have appeared in the distribution grids acting as distributed generators (DGs). By taking advantage of the flexibility of the control of power electronic converters, it has been possible to develop totally distributed as well as mixed centralized-distributed automation solutions for voltage regulation [56][57]. The technique consists in either rule based approaches [57] or optimization algorithms [56]. The possible control actions include changing the position of the OLTC, ordering the DGs to generate/consume reactive power, and ordering DGs to curtail their real power generation or “suggesting” loads to shade their consumption. The optimization algorithms to solve voltage contingencies in distributed active grids are of particular interest due to their peculiarity to be deployable by using distributed intelligence [56]. It is, in fact, possible to smartly dispatch the power of the DGs by taking into account the resistive-inductive characteristics of the distribution grid by involving the minimum number of DGs according to their sensitivity on the local voltage.

A major challenge with these converters is to ensure small-signal voltage stability under all dynamic conditions of load vs. generation. For such a reason, a novel system automation concept has to be formulated, implemented, and validated. In this novel automation concept, all the grid-connected converters will be able to perform online identification of equivalent impedances seen at their PCC on the top of their power conversion function. The technique is called the Wideband System Identification (WSI) and it is recognized to be a non-invasive technique to identify AC power impedances [58]. The WSI technique, schematically represented in **Figure 23**, uses a short-duration small-signal Pseudo Random Binary Sequence (PRBS), i.e. a digital approximation of white noise which is wideband in nature, injected on the control loop of the grid-connected converter. By doing this way, the frequencies of interest (10 Hz – 20 kHz) are excited at once at the PCC, and by performing post-processing on the measured voltage and current the parametric impedance can be calculated online. This parametric impedance is presented in the following form:

$$Z_{ref\_frame} = \frac{a_0 + a_1 s + \mathrm{L} \ + a_{n-1}s^{n-1} + s^n}{b_0 + b_1 s + \mathrm{L} \ + b_{m-1}s^{m-1} + s^m} \tag{2}$$

Where *reframe* is the chosen reference frame on which the identified three-phase impedance is represented (i.e., either *dq* or *abc*). In the novel automation concept, the identified parameters, i.e. the coefficients of the numerator and denominator of the transfer function (2), are then provided to a central unit (most likely located at the substation level) to perform online stability analysis. At this stage, the central unit online calculates the stability margins of an impedance-ratio-based system-level loop gain (similarly to the Middlebrook Criterion and its extensions formulated for DC system [60]), which is going to be formulated in WP3. The central unit has also the duty to coordinate the system-level PRBS injection mechanism in order to minimize the risk for undesired interactions. The result of the small-signal stability analysis will be translated into a system-level impedance profile that all grid-connected converters should have to guarantee the overall stability of the system. This information can then be fed back to the grid-connected inverters via the concept of Virtual Output Impedance (VOI) [61], i.e. an active method to shape the output impedance of power converters by acting on their control algorithms.

The novel automation concept based on online monitoring of AC power impedances and VOI will present the following advantages:

1) It will allow operating the distribution grid in a more efficient way because it will avoid losses due to implementations of injection of reactive power where the hypothesis R<<│X│ adopted by TSOs to solve voltage issues does not hold in distribution, and

2) It will require neither the installation of extra sensors nor smart meters because the WSI technique just uses the existing sensing equipment of the grid-connected converters and it does not require to extract customers' private information (like with smart meters) because of the fundamentally abstractness of an impedance measurement.

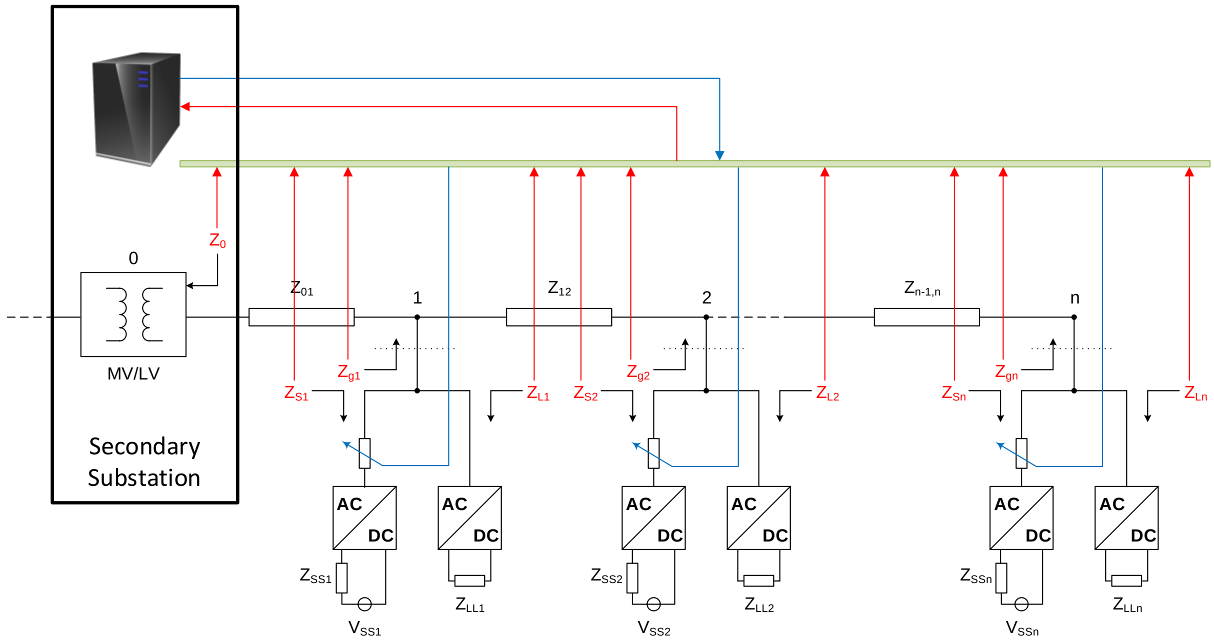


Figure 22 Power-Electronics-based LV Feeder with equipped with the communication architecture to perform stability analysis at substation level and provide set-points for the virtual impedance of grid-connected inverters.

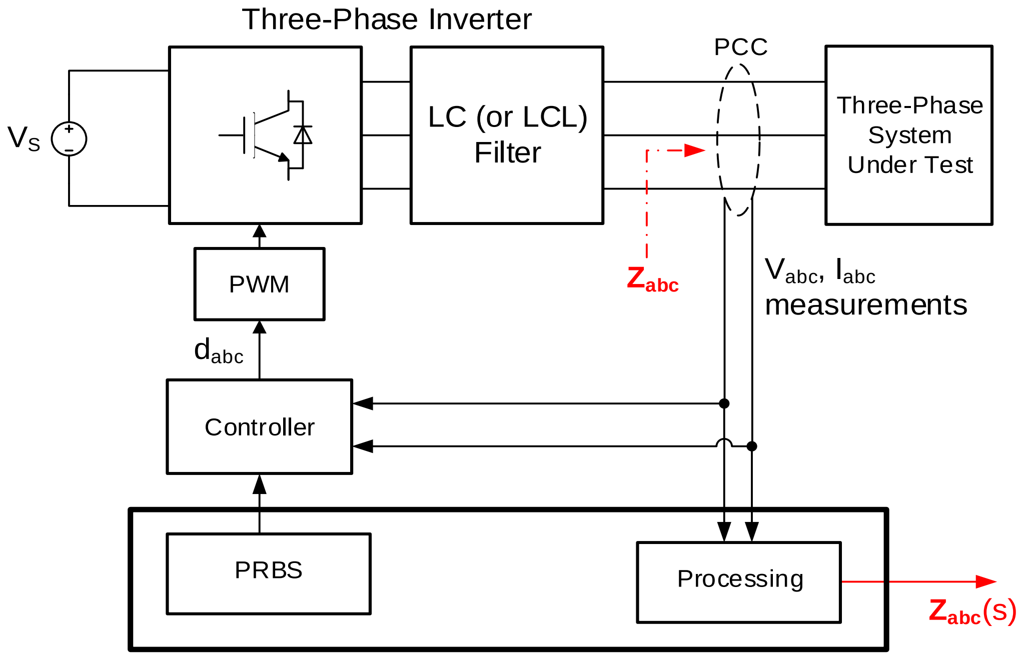


Figure 23 Conceptual block diagram of the WSI technique.

5. Information Systems for Developing 100% RES

The utility industry is rapidly modernizing and with the advent of high renewables penetration, as suggested by RE-SERVE scenarios, the rapidly changing topologies, distribution and transmission analysis will require different information technology techniques and tools both from those available today and those showing promise for the future.

Given that RE-SERVE is looking at frequency stability issues where support for virtual-synthetic inertia control strategies will be required and voltage stability issues addressed with the Wideband System Identification (WSI) technique wherein online stability analysis is carried out at the substation level and the system-level PRBS injection mechanism will have to be coordinated inter-substation, in order to minimize the risk for undesired interactions it is clear that accuracy, data transfer, and data processing abilities are key, and measured data sources must be handled in both slow-changing and fast-changing environments. Modeling tools need to be calibrated based on measured grid data to validate their output in varied conditions and it is clear that a standardized data modeling format, such as CIM [59], would enable all utility industry actors to transfer data among tools to take advantage of different analysis features.

The main purpose of this section is to provide an overview of information system solutions which could be applicable to utility use cases for power grid balancing scenarios based on up to 100 % RES generation.

5.1 Information System Platform Architecture

In order to generically specify an information system, it is worth considering **ARCADE** "An Open Architectural Description Framework" [60] which is a domain and technology independent architectural description framework for software intensive systems. ARCADE uses the following definitions from the Systems and software engineering - Architecture description [61] for the central concepts of architecture and architectural description:

- Architecture: The fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution.

- Architectural Description (AD): A collection of products to document an architecture.

ARCADE provides a set of viewpoints, with each view consisting of one or more models that describe and present different aspects related to structure and behavior of an information system.

ARCADE also provides a generic reference architecture which can be specialized and refined for specific application types and specific domains, case in point the 100% RES platform solution. The reference architecture divides the target system into a set of logical tiers, and defines how the system interfaces with the environment. A tier is a logical partitioning of a system where each tier has a unique responsibility. Each tier is loosely coupled to the tiers directly above and below. The tiers defined in the reference architecture are:

User Interface (UI) tier: The user interface tier provides user interaction logic through a set of user interface components. It communicates with the user service tier.

User Service (US) tier: The user service tier provides the user's model, which may include user session logic and user-side representations of processes and information. It is an abstraction for a set of business services, making the business service provision transparent for the user interface tier. The components at this tier can be divided broadly into entity and service components, where the entities represent information as it is presented to users.

Business Service (BS) tier: The business service tier provides service components that represent business functionality and also pervasive functionality. This tier provides enterprise-level services, and is also responsible for protecting the integrity of enterprise resources at the business logic level. The components at this tier can be divided in entity and service components, where the entities directly represent persistent business information.

Resource Service (RS) tier: The resource service tier provides global persistence services, typically in the form of databases, and messaging servers. Resource adapters provide access, search and update services to databases and its data stored in a database management system.

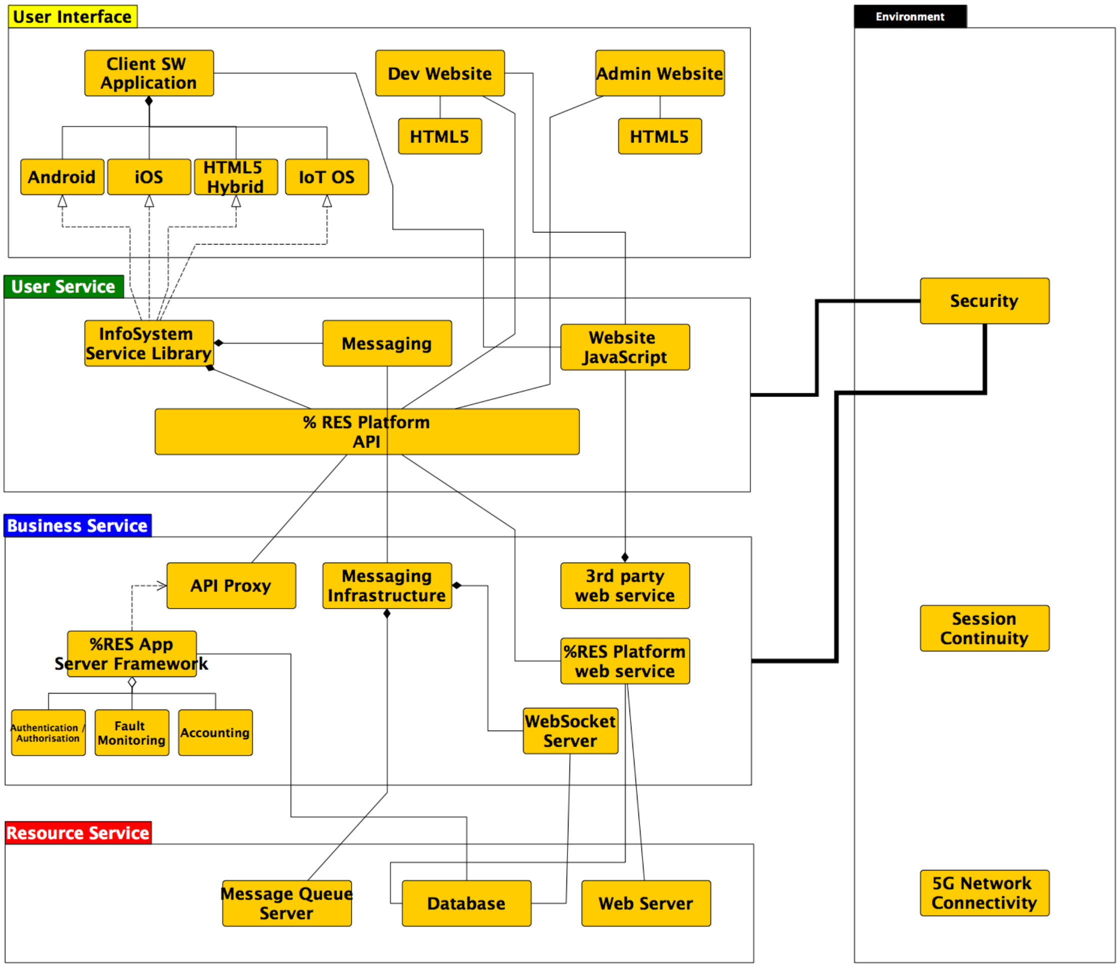


Figure 24 An Open Architectural Description Framework (ARCADE)

In delivering on this information system reference architecture in the 100% RES context, the most interesting aspects are the service orientation of the architecture and the techniques of the business service tier and the tools of the resource service tier.

5.1.1 Service orientation: Micro-services architectural style

The software engineering community have advocated for many years the service-orientation principle, where the logic required to solve a large problem can be better constructed, carried out, and managed, if it is decomposed into a collection of smaller and related pieces, each of which addresses a concern or a specific part of the problem. Service-Oriented Architecture (SOA) encourages individual units of logic to exist autonomously yet not isolated from each other. Within SOA, these units are known as services [62].

SOA has provided an effective solution to coordinating computational resources across heterogeneous systems to support various application requirements. As described in [63], SOA is an architecture within which all functions are defined as independent services with evocable interfaces that can be called in defined sequences form business processes.

However, there has been a lot of excitement around the microservices architecture, which started out as a mere undercurrent in the overall IT conversation, but is now gaining significant momentum. The microservices architectural style is an approach to developing a single application as a suite of small services, each running in its own process and communicating with lightweight mechanisms, often an HTTP resource API (RESTful API). These services are built around business capabilities and independently deployable by fully automated deployment machinery, which will be explained further in the following sections. There is a bare minimum of centralized management of these services, which may be written in different programming languages and use different data storage technologies [64].

In microservices, each operation is developed separately with each microservice free to independently incorporate changes only when needed. Each microservice can be independently deployed, stopped, or restarted on its individual application node. In addition they can be deployed independently [65], but with a heavy emphasis on the use of automated testing and automated deployment and the application must be able to deal with the failure of any service any time, therefore supporting automatic restart, monitoring and re-deployment.

5.2 Business Service Tier: Information System Techniques

Given that we are advocating the micro-services architectural style then no one application server framework can be chosen as it will all be down to the information processing problem and the development team behind that solution to choose. There are a number of advanced frameworks based on the Java programming language and the NodeJS javascript programming language with Node.js being hugely popular.

While there is a long understanding value of "*Big Data*" to better understand events, there is an alarming trend of Big Data envy, in which organizations are using complex tools to handle "not-really-that-big" Data. Distributed map-reduce algorithms are a handy technique for large data sets, but many data sets could easily fit in a single-node relational or graph database. Even with large data sets, more often than not the best thing to do is to first take a realistic assessment of what data needs to be processed, before large Big Data clusters are spun up. In support of this technique a "*Data Lake*", an immutable data store of largely unprocessed "raw" data, acting as a source for data analytics. This leads to accommodating machine- learning and implementing deep-learning algorithms helping to make better sense of the data sets.

There is continued adoption and success of reactive architectures, with reactive language extensions and reactive frameworks being very popular. User interfaces, in particular, benefit greatly from a reactive style of programming. However, there is a caveat to note architectures based on asynchronous message passing introduce complexity and make the overall system harder to understand.

Serverless architecture replaces long-running virtual machines with ephemeral compute power that comes into existence on request and disappears immediately after use. Examples include Firebase [74] and AWS Lambda [75]. Use of this architecture can mitigate some security concerns such as security patching and SSH access control, and can make much more efficient use of compute resources. These systems cost very little to operate and can have inbuilt scaling features (this is especially true for AWS Lambda).

There is a continued rise to domination of the container model led by Docker [76] adoption, as it evolves from a tool to a complex platform of technologies. The Docker image format makes it easier to achieve parity between development and production, making for reliable deployments. It is a natural fit in a micro-services-style application as a packaging mechanism for self-contained services. Orchestration and management of deployed containers is an issue, with Kubernetes a possible solution to deploying containers into a cluster of machines, which is becoming an increasingly common scenario.

It is also worth calling attention to the continued rapid development in the Unikernel [77] space. Unikernels are single-purpose library operating systems that can be compiled down from high-level languages to run directly on the hypervisors used by commodity cloud platforms. They promise a number of advantages over containers, not least their superfast startup time and very small attack surface area.

Within this business services tier an API Gateway is an essential element to enable developers to expose API services to Internet clients, offering features like traffic management, monitoring, authentication and authorization. More often than not this API Gateway supports a RESTful service API, as the RESTful API has emerged in the last few years as a predominant web service design model mostly displacing SOAP- and WSDL-based interface design because it's a considerably simpler style to use.

Although it should be noted that a review of REST implementations in the wild, it can be seen that REST is misused to naively retrieve object graphs through chatty interactions between the client software and server. GraphQL [78] is an interesting alternative to REST that might be a better approach for this very common use case. As a protocol for remotely retrieving object graphs, GraphQL features a consumer- oriented model, where the structure of a response is driven entirely by the client, not the server. This decouples the consumer and forces the server to obey Postel law “be conservative in what you send, be liberal in what you accept”. This in turn empowers clients to build mostly-working complex networked systems without coordinating with others or asking permission to implement it in a certain way.

5.3 Resource Service Tier: Information System Tools

Given the timing constraints in the power electronics world of 100% RES, then new data architectures that capture information as an immutable sequence of events (for example through Apache Kafka [79]) or platforms for scalable distributed batch and stream processing (for example Apache Flink [80]) need to be considered in the resource service tier.

When it comes to the immutable sequence of events, or for want of a better wording the “*logging*” of events, instead of modifying the state of the application in-place, event sourcing involves storing the event that triggers the state change in an immutable log and modeling the state changes as responses to the events in the log. Apache Kafka is a fast, scalable, durable, and fault-tolerant publish-subscribe messaging system that is often used in place of traditional message brokers like JMS [81] and AMQP [82] because of its higher throughput, reliability and replication. Kafka works on the real-time analysis and rendering of streaming data from smart sensors and can broker massive message streams for low-latency analysis in a “Big Data” or “Data Lake” environment.

Scalable distributed batch and stream processing addresses the demand for faster data processing, optimized for cyclic or iterative processes by using iterative transformations on collections. This is achieved by an optimization of join algorithms, operator chaining and reusing of partitioning and sorting which increases the possibility of real-time stream data processing and important factor in 100% RES system.

From a security perspective, trying to combat botnets is hard and the platform must be protected from distributed denial of service attacks (DDoS) and a tool like “Deflect” [83] as a distributed reverse-proxy caching server that also hides the platforms server IP addresses and blocks public access to admin URLs is a must.

With the number of high-profile security breaches increasing per month, Threat Modeling provides a set of techniques that help identify and classify potential threats early in the development process. It is important to understand that it is only part of a strategy to stay ahead of threats. When used in conjunction with techniques such as establishing cross-functional security requirements to address common risks in the technologies a project uses and using automated security scanners, threat modeling can be a powerful asset

With the growth in usage of NoSQL data stores, and the growth in popularity of polyglot approaches to persistence, information system teams now have many choices when it comes to storing data.

SQL databases are primarily called Relational Databases (RDBMS), whereas NoSQL databases are primarily called non-relational or distributed database. With SQL databases the emphasis is on ACID properties (Atomicity, Consistency, Isolation and Durability) whereas the NoSQL database follows the Brewers CAP theorem (Consistency, Availability and Partition tolerance). With SQL databases scaled by increasing the horse-power of the hardware, whereas NoSQL databases are scaled by increasing the databases servers in the pool of resources to reduce the load there is special consideration between the two.

SQL database examples include: MySql, Oracle, Sqlite, Postgres and MS-SQL. NoSQL database examples: MongoDB, BigTable, Redis, RavenDb, Cassandra, Hbase, Neo4j and CouchDb.

While choice of SQL/NoSQL has brought many advantages, product behaviour with different types of network connectivity can introduce subtle and not so subtle issues, and an understanding of how different database and queuing technologies react under different connectivity conditions has to be explored.

While open source web servers like Apache [84] and NGINX [85] have proven themselves in production field deployments, attacks on these types of web servers using botnets are becoming more sophisticated. Identifying these bad actors and their behaviors as they pertain to Apache or NGINX webservers is a must. Tracking user activity, fingerprinting actors using predefined and user-defined rules, and then allowing action to be taken, including the ability to block offensive actors is a must.

6. 4G and 5G based ICT features for RE-SERVE solutions

This section of the deliverable provides and overview of 4 and 5G based ICT features which could provide communication and IT facilities particularly useful to utilities as they migrate towards use cases for power grid balancing scenarios based on up to 100% RES power generation. The RE-SERVE project will develop concepts for and investigate, optimise and demonstrate the use of a range of 4 and particularly 5G features in the context of power grid management based on up to 100% RES generation. Hence, developing an understanding of how the new communications facilities could contribute to power grid management is a key objective of the RE-SERVE project and this chapter provides an overview of the features of 4 and 5G systems. An outcome of RE-SERVE will be recommendations for communications solutions for utilities as they transition to ever higher levels of RES.

6.1 Towards new mobile communications system and device features

The low latency of the communications, the low cost of devices and the introduction of new features such a software defined communications, network feature virtualization and local edge processing will enable new schemes for the monitoring and control of power networks, particularly in distribution networks, in which utilities need to deploy increased levels of power monitoring and control devices and systems.

Throughout a range of industries, a wave of change can be observed. Smarter ways of working based on interconnecting devices, systems and platforms are being adopted. This transformation sets requirements on connectivity and sets the scene for the next generation of wireless access – 5G systems. 5th Generation cellular networks will be designed to incorporate machine centric communication along with human centric communications.

5G (5th Generation cellular mobile communications network) is currently in the international standardization and prototype development phase. Products will be available on the global markets, based on international standards, from 2020 onwards.

5G builds on and is compatible with 4G (4th Generation cellular mobile communications network known as LTE, Long Term Evolution), 3G (UMTS) and 2G (GSM) networks. 4G (LTE) is still evolving and new networking features coming on the market as products are described at the beginning of this chapter. Then 5G and advances in IoT (Internet of Things) devices are described as the new network and devices have many features which make them suitable for utility use cases (e.g. 10 year + battery life and penetration of signals down to two floors below ground).

6.2 LTE (4G) Mobile Communications

Long Term Evolution (LTE) is 4th generation of mobile communication technology, standardised by 3GPP (3rd Generation Partnership project). In contrast to the circuit-switched network of previous generations, LTE has been design to support fully packet-switch services. At the end of 2007, first LTE standard was introduced by 3GPP standardisation body names as LTE release 8.

LTE can provide high speed data rates as well as support for high speed mobility:

- The LTE specification provides downlink peak rates of 300 Mbit/s, uplink peak rates of 75 Mbit/s and QoS provisions permitting a transfer latency of less than 5 milliseconds in the radio access network.
- LTE supports flexible carrier bandwidths (1.4 MHz to 20 MHz) along with providing both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) options to separate downlink and uplink communication. In FDD, uplink and downlink transmission are done using different frequencies, while in TDD, both side transmission are done on same carrier with separated time [86].

LTE has been continuously evolved to enable new use cases pertaining to machine centric communication. Starting from release 12, new features have been defined and more modification are being done to enable LTE technology to adapt to new network aspects for new use cases.

6.2.1 LTE Network overview

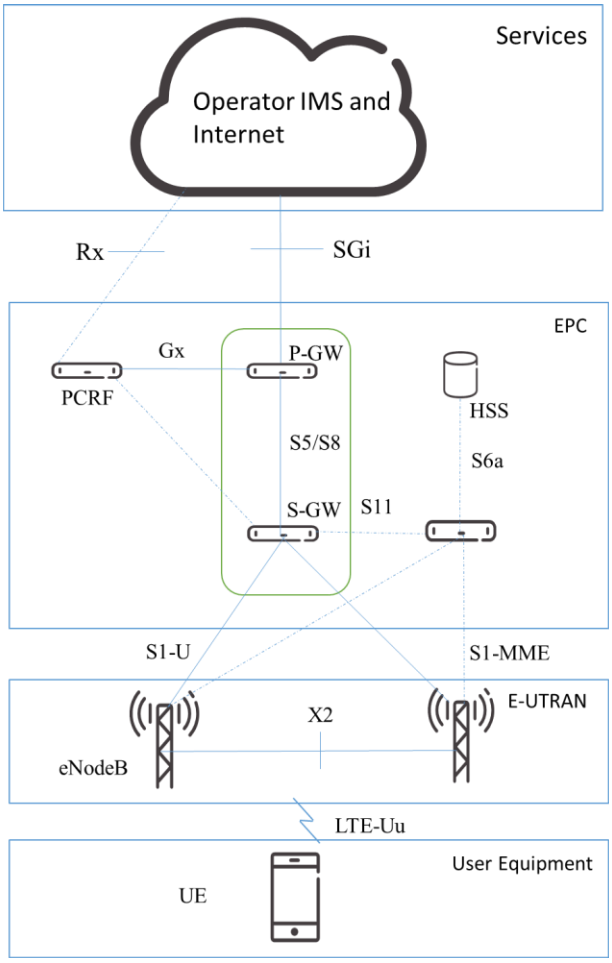


Figure 25 LTE Network Architecture

A simplified IP-based network architecture is adopted in LTE. It is divided into four domains. Figure 25 provides visualization of LTE network architecture.

1. **User Equipment (UE)**
   - Radio transceiver providing air interface to end user

2. **Evolved -Universal Terrestrial Access Network (E-UTRAN)**
   - Radio access network consisting of eNobeB's responsible for radio related functions. More specifically, function includes radio resource management, QoS provisioning, scheduling, ciphering/deciphering and admission control. eNodeB hosts Physical, Medium Access Control (MAC), Radio Link Control (RLC) and Packet Data Control Protocol (PDCP) layers.

3. **Evolved Packet Core (EPC)**
   - EPC is responsible for charging, setup of end to end connections and all other functions that are not related to radio interface. EPC also provide connectivity other non 3GPP/3GPP networks. The main logical nodes of the EPC are:

     - Packet Data Network Gateway (P-GW): This entity is responsible for allocating IP address for terminal and QoS enforcement. It is main anchor for non-3GPP radio access network

- Service Gateway (S-GW): It is responsible for handling user traffic routing and forwarding data packets. It terminates the interface towards E-UTRAN and acts as mobility anchor for inter eNodeB handovers.
- Mobility Management Entity (MME): It is key node for handling control signaling and is responsible for authentication and security parameters configurations. It is connected to Home Subscriber Service (HSS) node, a database containing subscriber information.

6.2.2 LTE Enhancements

The first major steps in the evolution of LTE also referred to as LTE-A occurred as part of 3GPP release 10. It was finalised 2010. Release 10 extended and enhancement the LTE radio-access technology covering different aspects. The most important feature was the introduction of carrier aggregation to improve the possibility of exploiting fragmented spectrum allocation and to support wider bandwidth and consequently higher data rates than initial LTE releases.

Currently, 3GPP is working on release 13. This release will improve and enhance LTE in several aspects, and strengthen its capacity to serve as a platform for the Network Society by providing data access and sharing anywhere and anytime. Whereas the first mobile communication system offered voice services, today's LTE network offer mobile broadband services that include video streaming and media delivery. In this context, not only higher peak data rates are of interest but also availability of sufficiently high data rates are of interest. In addition to performance requirement from current and future human-centric applications, new use case pertaining to machine centric applications such as proximity, public safety, machine critical communication result in very wide range of requirements.

Consequently, mobile broadband enchantments and expansions into new use cases are foreseen to be in the scope of LTE release 13. More specifically, enhancement addressing network capacity and user experience for mobile broadband includes:

6.2.2.1 Licensed Assisted Access (LAA)

LAA is the use of Wi-Fi unlicensed spectrum with the assistance from licensed spectrum that is primary carrier from the mobile network. The local Wi-Fi is considered as secondary carrier which carries data transmissions.

6.2.2.2 Carrier-Aggregation Enhancements

In LTE Carrier aggregation allows the mobile operator to use their spectrum more efficiently to boost user throughputs and increase capacity. In 3GPP release 13, enhancements in carrier-aggregation allows to handle up to 32 carriers both direction uplink and downlink. This means, LTE terminals will be able to handle bandwidths of 640MHz.

6.2.2.3 Multi-Antenna Enhancements

Multi-antenna techniques such multiple-input and multiple-output (MIMO) spatial multiplexing is used to improve spectral efficiency. In 3GPP release 13, two-dimensional base station antenna arrays with up to 64 antenna ports are introduced to exploit both the azimuth and elevation domains.

6.2.2.4 Latency Reduction

Lower Latency was a key requirement in the development of LTE. In past couple of releases on 3GPP, data rates are increased a lot and therefore 3GPP in release 13 and beyond are standardizing enhancements to reduce latency. The technologies being standardized are instant uplink access, transmission-time interval shortening and reduction in processing time in base stations and terminals.

Furthermore, the expansion into new use cases include:

6.2.2.5 Machine Type Communication

In the vision of Networked Society, the number of machines communicating are increasing dramatically. These machines are sending and receiving information via LTE network. MTC is very broad term with vast requirements depending on the use-cases. For machine type communication, there are a lot LTE enhancements going on, such as:

- Reduced device cost
- Reduced power consumption
- Handling massive number of devices

6.2.2.6 Device to device communication

Device-to-device communication was first introduced in 3GPP release 12 as a part of LTE. It is intended to provide basic functionality of LTE for public safety as well as in-coverage discovery for commercial use cases. Device to device communication now allows out-of-coverage, multi-carrier support for discovery of the devices and relaying solutions to extend coverage.

6.3 5G Mobile Communications

The main driving force behind the development of 5G is to support a wide range of use-cases such as augmented reality, logistic tracking, energy meter reading and updating, cell automation, smart factory operation and smart transport. In future smart grids and industrial use-cases will require ICT infrastructure supporting ultra-low latency, high availability, reliability and longer battery life. These requirements set the scene for next generation of wireless access – 5G systems – which are set for commercial availability in 2019. Figure 26 shows how LTE is evolving. Key components of 5G, such as Network slicing, E2E security, NFV, new Radio Access and SDN will be useful in developing new solutions for communications and control of power grids as we move towards up to 100% RES.

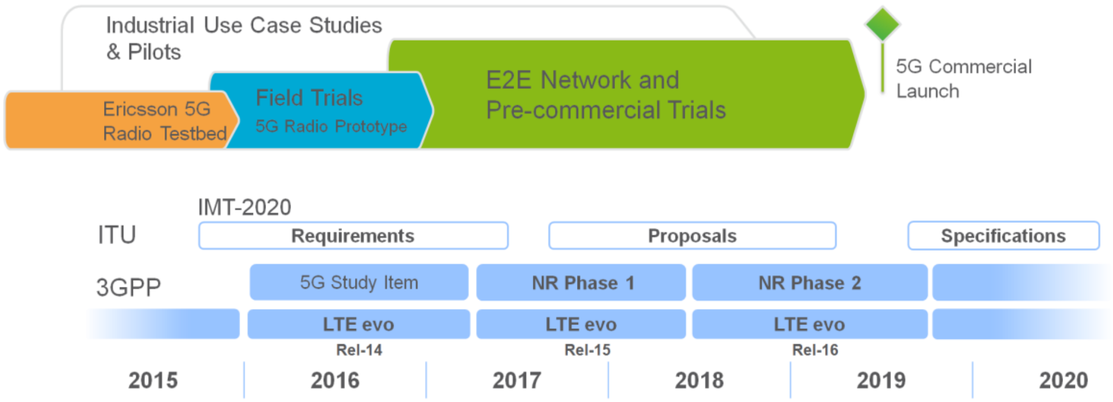


Figure 26 5G system development time line

6.3.1 5G Key Enablers

5G systems will be built with key technologies for managing logical rather than physical resources. These technologies enable us to utilize 5G as a communication technology for RE-SERVE solutions. The following sub-sections provide detail descriptions of such technology key enablers.

6.3.2 Software-defined networking (SDN)

The benefit of SDN lies in its ability to provide an abstraction of the physical network infrastructure. Through network-wide programmability – the capability to change the behavior of the network as a whole: SDN greatly simplifies the management of networks.

The level of network programmability provided by SDN allows several network slices, customized and optimized for different service deployments, to be configured using the same physical and logical network infrastructure. One physical network can therefore support a wide range of services and deliver these services in an optimal way.

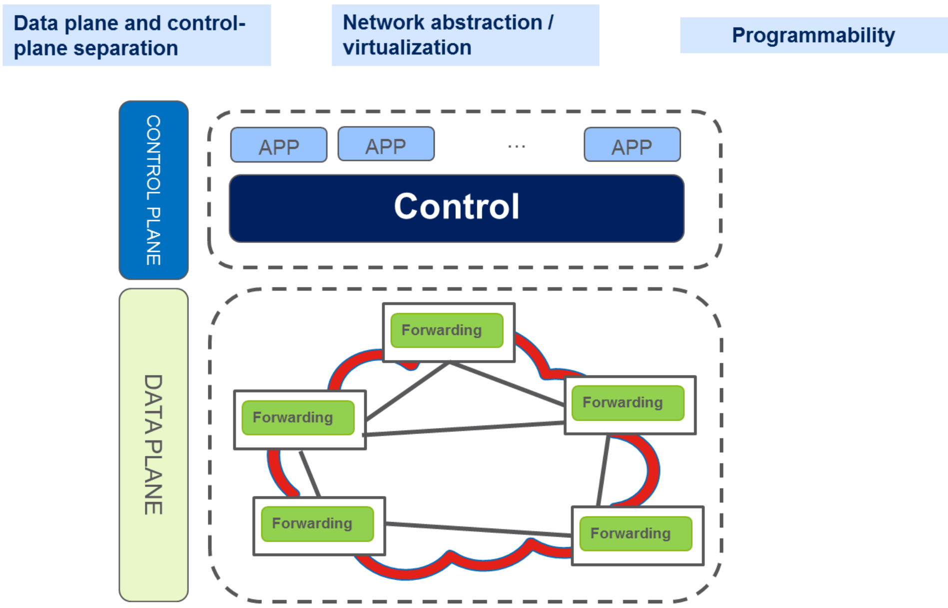


Figure 27 Software Defined Network Concept

6.3.3 Network Functions Virtualization (NFV)

By separating hardware from software, NFV allows a network function to be implemented programmatically instead of by a physical piece of hardware. This capability enables instant scalability, which supports the delivery of services like capacity or coverage on demand.

The most significant benefit brought about by NFV is the flexibility to execute network functions independently of location. By virtualizing a network function, it is no longer bound to a specific location or node. The same network function can be executed in different places for different network slices. Depending on the use case, a network function could either be placed in a centralized data center (DC) or close to a base station. By placing network functions accordingly, the same physical infrastructure can provide connectivity with different latencies.

6.3.4 5G Radio Access

To provide the wide range of future wireless use cases with customized connectivity, 5G systems need to be based on a flexible radio-access solution that can adapt to different requirements and deployment types.

In terms of spectrum, 5G systems will need to be able to operate over a very wide frequency range from below 1GHz up to and including millimeter wave (mmW) frequencies.

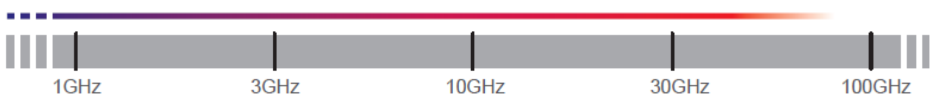


Figure 28 Spectrum range for 5G use cases

Lower frequencies will remain a key part of the spectrum used to deliver 5G network capabilities such as very low latency, ultra-high reliability and high data rates with wide-area coverage. This range will be complemented by high-frequency deployments – above 10GHz – that will be able to deliver extreme data rates and extreme capacity in dense areas (3GHz 1GHz 10GHz 30GHz 100GHz).

Operation under different spectrum-assignment regimes will enable 5G systems to provide greater flexibility. Since its inception, cellular communication has relied on dedicated licensed spectrum, and this will remain the case for 5G systems, in order to meet the need for delivering high-quality connectivity with very high availability. However, the use of dedicated licensed spectrum will be extended to operate with more flexible spectrum assignment. For example, Licensed Shared Access (LSA) will enable spectrum sharing across industries, and licensed-unlicensed spectrum combinations can be operated through Licensed Assisted Access (LAA). By using carrier aggregation technology, LAA enables mobile devices to leverage the combination of both licensed and unlicensed spectrum bands.

In terms of technology, LTE will continue to evolve, and will be an important part of the overall 5G wireless-access solution – providing a backward-compatible path for 5G capabilities in LTE spectrum. In parallel, new RATs will emerge, initially targeting new spectrum where backward compatibility to existing technology is not an issue. New spectrum will primarily be available in the higher frequency bands above 10GHz. However, new spectrum may also partly become available in lower frequency bands. On a longer timescale, new RATs may migrate into LTE spectrum.

A high level of interworking between LTE evolution and new RATs is needed to ensure that 5G functionality can be introduced smoothly. Such interworking will include dual-connectivity where, for example, a device will maintain simultaneous connectivity to a dense high-frequency layer providing very high data rates as well as to an overlaid lower-frequency LTE layer that provides ubiquitous connectivity. User-plane aggregation between LTE and any new radio technology is another example of the high level of interworking.

Additional key technology components for the 5G radio-access solution include:

- advanced multi-antenna technologies,
- ultra-lean transmission to maximize resource efficiency,
- flexible duplex,
- access/backhaul integrations, where access and (wireless) backhaul share the same technology and the same overall spectrum pool, and
- well-integrated device-to-device communication.

These technology components will not only apply to the new technology part of the 5G wireless-access systems but will, to a large extent, also be applicable to the evolution of LTE enabling the features of the currently available public and private networks to be upgraded.

6.3.5 5G Management and Orchestration

Operators, as well as enterprises, want to deliver and operate services at the lowest possible cost without compromising quality. To do this, management entities in 5G systems will need to be able to automate and orchestrate provisioning processes, as well as be capable of coordinating cloud resources for complex dynamic systems that require resource access control and service quality management. Given the increasing demand for Service Level Agreements (SLAs), the network needs to play a more active role in delivering reliability and performance guarantees.

Orchestration enables automation across the building blocks of a network through centralized management of network resources.

To offer services that draw resources from several building blocks, E2E orchestration is needed to match external business offerings with network efficiency. To optimize media delivery, for example, orchestration would place virtualized network functions on resources that are physically close to the subscriber.

New technologies will be needed so that 5G systems will be able to cope with the increased load. This includes technologies and methods for improving performance and operation of the 5G system through data analytics, including:

- enhancement of RAN features based on data analytics,

- automation – self-organizing networks and data analytics features for operations support systems and network management systems, and
- automation and data analytics technologies for network operations centers.

6.3.6 5G Energy Performance

Networks need to be energy-focused on two fronts: reduced energy consumption of all network resources to lower operational cost, and increased battery life to enable massive deployment of sensor networks.

Wide area coverage dominates network energy consumption, and studies show that for LTE, approximately 50 percent energy savings are possible without compromising coverage and while still meeting the increased – 1,000 times – traffic demand in 5G.

Applications and services must be built with smart information so that M2M devices can sleep for as long as possible, only waking up when the information they possess is actually needed.

6.3.7 5G spectrum

In order to support increased traffic capacity and to enable the transmission bandwidths needed to support very high data rates, 5G will extend the range of frequencies used for mobile communication. This includes new spectrum below 6GHz, as well as spectrum in higher frequency bands.

Spectrum relevant for 5G wireless access therefore ranges from below 1GHz up to approximately 100GHz.

It is important to understand that high frequencies, especially those above 10GHz, can only serve as a complement to lower frequency bands, and will mainly provide additional system capacity and very wide transmission bandwidths for extreme data rates in dense deployments. Spectrum allocations at lower bands will remain the backbone for mobile-communication networks in the 5G era, providing ubiquitous wide-area connectivity.

The mobile industry will strive to gain access to spectrum in the 6GHz to 20GHz range, but the policy directions being followed by regulators seem to be focused on frequency bands above 30GHz. In the US, the FCC has issued two Notices of Public Rule Making (NPRM) on bands above 24GHz. Ofcom has likewise indicated a preference for bands above 30GHz within the mobile industry.

6.4 Comparison of Mobile Network capabilities from 2G to 5G

2G, 3G, 4G and 5G communications all offer useful features to utility use cases. Therefore, a comparison of the different mobile networks capabilities is shown in Table 9 to provide a comparative overview of their capabilities.

Table 9 Cellular Networks comparison [87][88][89][90]

	GSM (2G)	**UMTS / HSPA+ (3G)**	**LTE (4G)**	**5G [under discussion in standardization body]**
Frequency Bands	450/800/900 MHz, 1.8/1.9 GHz	850/900 MHz; 1.7/1.9/2.1 GHz	700,800MHz, 850/900MHz, 1.7/1.8/1.9/2.1/2.3/ 2.5/2.6/3.5 GHz	1GHz – 100GHz
Channel Bandwidth	200 KHz	5 MHz, 10MHz	1.4, 3, 5, 10,15 and 20 MHz	100MHz
Modulation	GMSK	QPSK (+ 16QAM and 64QAM for	QPSK, 16QAM and 64QAM	Higher modulation 256QAM

		HSPA)		
Channel Coding	Convolutional Coding	Convolutional Coding	Convolutional, Turbo and LDPC Coding	Low density parity check (LDPC) coding
Multiple Access Scheme	TDMA, FDMA	CDMA, TDMA	OFDMA, SC-FDMA	OFDM
Peak Data rate	9.6kbps	384kbps – 42Mbps	326Mbps	25Gbps
Round Trip Time	600	41ms – 75ms	20ms	Up to 3ms

6.5 IoT (Internet of Things) for industrial automation use cases

Connectivity is the foundation for the IoT, and the type of access required depend on the nature of the application Many IoT devices will be Many IoT devices will be served by radio technologies that operate on unlicensed spectrum and that are designed for short-range connectivity with limited QoS and security requirements typically applicable for a home or indoor environment. Currently, there are two alternative connectivity tracks for the many IoT applications that depend on wide-area coverage:

Cellular technologies: 3GPP technologies like GSM, WCDMA, LTE and future 5G. These WANs operate on licensed spectrum and historically have primarily targeted high-quality mobile voice and data services. Now, however, they are being rapidly evolved with new functionality and the new radio access technology narrowband IoT (NB-IoT) specifically tailored to form an attractive solution for emerging low power wide area (LPWA) applications.

Unlicensed LPWA: new proprietary radio technologies, provided by, for example, SIGFOX and LoRa, have been developed and designed solely for machine-type communication (MTC) applications addressing the ultra-low-end sensor segment, with very limited demands on throughput, reliability or QoS.

Broadly, machine type communication requirement can be divide into two part, massive MTC and Critical MTC. From the connectivity point of view, device to device communication and device to infrastructure communication solutions including LTE D2D communication technology solution will be realized depending on use case under consideration. Device to device connectivity allows data rate gain, low latency and efficient utilization of the radio resource by cellular offloading. LTE narrowband communications will be considered as part of the solution, depending on the use case in question.

Each of the technologies available for IoT connectivity has its advantage and disadvantages. However, comparing unlicensed LPWA and cellular, cellular technologies has clear advantages as summarized in Figure 29.

Figure 29 Advantage of cellular technologies

One of the important feature need to consider from IoT applications perspective is QoS mechanism. Cellular systems have mature QoS functionality and this enable critical MTC application to be handled together with traffic from sensors, voice, mobile-broadband traffic on the same carrier. Also QoS along with licensed spectrum as described above, provides a foundation for long-term Service Level Agreements.

Mobile telephony, mobile broadband and media delivery are about information for humans. In contrast, many of the new applications and use cases that drive the requirements and capabilities of 5G are about end-to-end communication between machines, these applications are often termed machine-type communication (MTC). MTC applications can be divided into two main categories – massive MTC and critical MTC – depending on their characteristics and requirements.

Massive MTC refers to services that typically span a very large numbers of devices, usually sensors and actuators. Both are low cost and consume very low amounts of energy to sustain long battery life, and the amount of data is normally very small, and very low latency is not a critical requirement.

Sometimes, the mobile network may be used to bridge connectivity to the device by means of capillary networks, by means of a short-range radio access technology, for example Wi-Fi, Bluetooth or 802.15.4/6LoWPAN.

Critical MTC refers to applications such as traffic safety/control, control of critical infrastructure and wireless connectivity for industrial processes. Such applications require very high reliability and availability in terms of wireless connectivity, as well as very low latency. While the average volume of data transported to and from devices may not be large, wide instantaneous bandwidths are useful in can meet capacity and latency requirements. Recently [95] enhancement in LTE radio access and new 5G radio interface design concepts are investigated for industrial automation use cases.

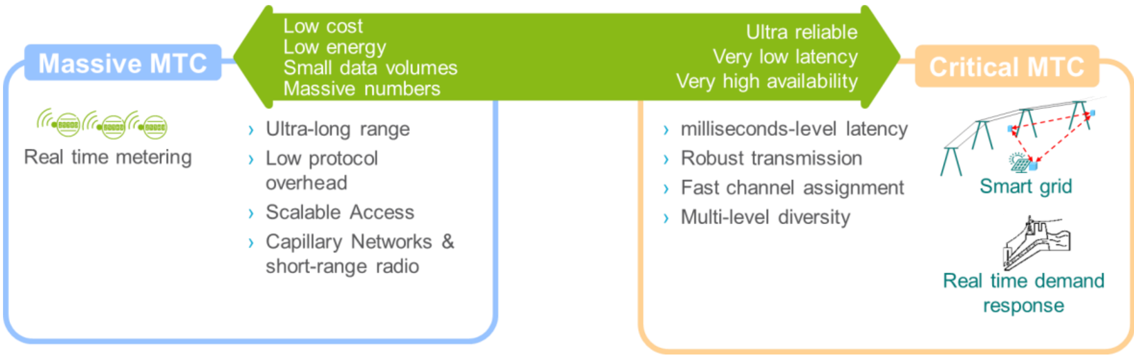


Figure 30 Machine type communication requirement

In order to support massive IoT connectivity, 3GPP in release 13 has considered key enhancement listed below,

1. Lower device cost: The LTE module cost reduction evolution started in release 8 with introduction of LTE for machine type communication (Cat 1) devices with reduced peak rate to a maximum of 10 Mbps, continued in Release 12 and release 13 with reduced device complexity,
2. Improved battery life: more than 10 years of battery life can be achieved by introducing Power Saving Mode and extended discontinuous reception (eDRX) functionality,
3. Improved coverage: an improvement of 15dB on LTE-M and of 20dB on NB-IoT and GSM, which give seven time increase in outdoor coverage and significantly improved indoor signal penetration, and
4. Support for massive number of IoT connection.

No single technology or solution is ideally suited to all the different IoT applications, mobile industry is standardizing several cellular LPWA technologies, including Extended Coverage GSM, LTE-M and NB-IoT as shown in Figure 31.

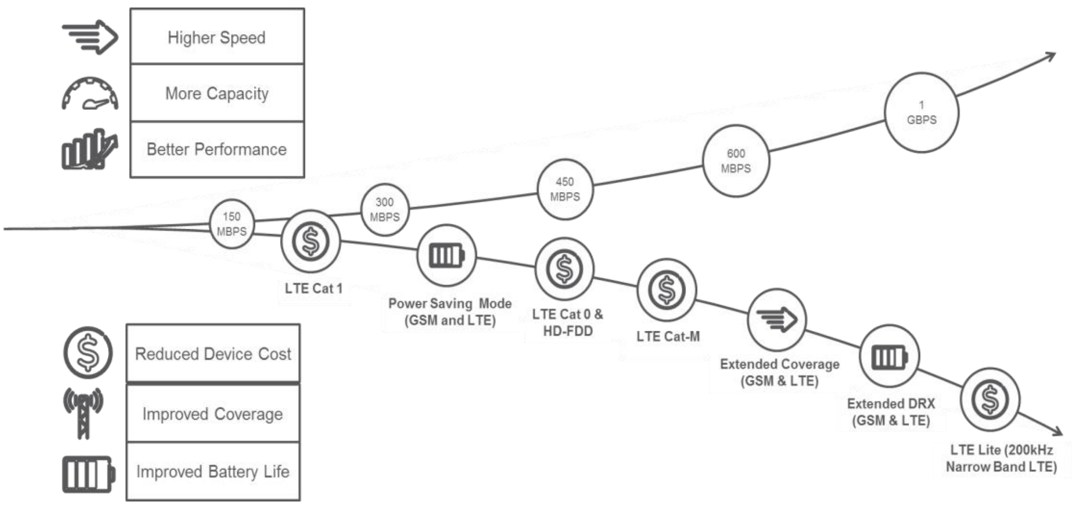


Figure 31 Device evolution for massive and critical MTC

Cat-1 – Category 1 – was included in the LTE specifications already in the beginning, Release 8. With a Cat-1 UE, it is possible to achieve 10 Mbps downlink and 5 Mbps uplink channel data rates. No MIMO is supported but the UE should still have 2 receiver antennas. Cat-1 has not been a relevant UE category for LTE-based mobile broadband services, as its performance is below the best 3G performance. Now it has become an attractive, early alternative for IoT applications over LTE, because it is already standardized. Cat-1 can also meet requirements of a wider range of MTC applications thus being a complementary solution to Cat-M1 and also to NB-IoT – which are explained further down.

Cat-0 – Category 0 – is one of the newest standardized categories from Release 12. Cat-0 UEs are intended for IoT use cases, and provide 1 Mbps data rates for both up- and downlink. Cat-0 UEs have reduced complexity by up to 50% compared to Cat-1; requirements include only one receiver antenna and support of half-duplex operation, providing ways for the manufacturers to significantly reduce the modem cost compared to more advanced UE categories.

Cat-M1 – Category M1 (which has informally also been referred to as Category M) – refers to the Release 13, where further complexity reduction techniques on top of the ones for Cat-0 are being standardized now. Up to 75-80% complexity reductions compared to Cat-1 have been indicated. The most important additional feature is the possibility to implement the UE transmitter and receiver parts with reduced bandwidth compared to normal LTE UEs operating with 20 MHz bandwidth. Cat-M1 UEs can operate anywhere within an LTE carrier with up to 20 MHz system bandwidth, but each Cat-M1 UE will operate with a maximum channel bandwidth limited to 1.4 MHz. A further helpful feature for many IoT use cases is coverage enhancements of more than 15 dB, which can, for example, be enabled to reach the UEs behind the thickest walls in the cell. Letter 'M' in the category name could be seen to stand for 'machine'. As the 3GPP work on MTC will continue, we may see further 'machine' categories in the future (like Cat-M2 and so on).

LTE-M, or LTE MTC, is not as well defined a term as the others in this article. It was originally used in the work which resulted in Cat-0 UEs, but further work conducted in 3GPP on enhancing LTE capabilities for IoT has since been included. In general, LTE-M can be used to refer to all use of LTE for M2M and IoT and the evolution of LTE MTC features. This includes both Cat-0 and Cat-M1 (even Cat-1) UEs, and other features such as Power Saving Mode (PSM) and extended DRX cycles (eDRX).

NB-IoT stands for Narrowband IoT and is a new narrowband radio technology being standardized in 3GPP. It covers all the components sought after: low complexity, low power consumption and long range. Some key characteristics include 180 kHz bandwidth and uplink and downlink data rates of about 200 kbps with half-duplex operation. Although this is a new radio interface, NB-IoT deployments can be made "inband", so that existing resource blocks in the LTE carrier are used. The term is not to be confused with LTE-M, which refers to more direct use of LTE evolution for MTC and IoT use cases. NB-IoT is subject to a lot of standardization activities at the moment, and it is possible – but not yet decided – that NB-IoT UEs will be referred to as Category M2 (**Cat-M2**) in the future. The complexity reduction compared to Cat-1 is up to 90%.

Note that both Cat-M1 and NB-IoT have been designed so that they would be competitive with today's cheap, GSM-based M2M modules. For example, for NB-IoT the initial module cost is expected to be less than $5

"EC-GSM-IoT, earlier referred to as EC-EGPRS, stands for Extended Coverage GSM for IoT. It includes the latest enhancements to the GSM and EGPRS standards to support better coverage and other IoT enhancements. EC-GSM-IoT supports 20 dB coverage improvements and can be deployed in the existing GSM networks."

6.6 Conclusion

In 21st century, connectivity will play important role in industrial transformation, particularly in the power sector. Technology such as 5G and IoT will play a major role in such transformations. Starting from LTE communication technology, mobile industry is advancing to 5th Generation cellular networks to provide focused support for machine centric communication as well as human centric communications. The chapter gives an overview of current advances in mobile and wireless communications and systems. A range of the features described in this chapter will be used in simulations and experiments with live communication networks as part of RE-SERVE so that their usefulness and performance in a range of use-case scenarios developed by the RE-SERVE partners can be evaluated, optimised and finally proposed as solutions to utilities as they move towards up to 100% RES generation.

7. Multidimensional framework for scenarios design

The introduction a multidimensional approach is a common way to proper handle the variety of inputs that one has to consider when characterizing a study case. In our case, the introduction of different dimensions allowing us the quick identification of the main characteristics of the introduced scenarios, as well as the presentation of comprehensive overview of the crucial areas and issues in managing high RES penetration grids starting from reference studies.

For passing from the theoretical problem to a description of possible scenarios, we need to detail them enough for using them as starting point of our SGAM analysis. We define these starting points as high level scenarios.

In [1] the presentation (for a complete mapping) of a description of the elements to be defined by this starting point. In our case, we will use SGAM analysis for the same reason and the description of our use cases do not need a high level of detail.

The main information needed include [1]:

- Actor names and types considered[4] Functional and non-functional requirements
- Preconditions, assumptions and eventual steps in the analysis

For sake of clarity, we build a dimensional framework, identifying the most relevant dimensions and sub-dimensions to bridge theoretical general point of view to the practical characteristics. All the features describe basic characteristics of the grid, taking into account the successive need of simulation and the use of test-beds. As explained in next chapter, the dimensions can be categorized in four main groups, aiming both to provide enough information and incorporating all the relevant elements of the project. In particular, we identify the main components and the basic architecture of the various domains of the grid (D1 to D4), the most interesting functions (D5, D7, D11) and the type of analysis focus (D5, D6, D9). In particular, D1 and D4 want to clarify the generation mix and account for the presence of new generation/producers into the grid, whereas D2 and D3 deal with the basic architecture of transmission and distribution grids. D11 refers to the possible contribution of ICT in the electricity system. New insight will be gained in Deliverable 1.2 and Deliverable 1.3.

Figure 32 and Figure 33 show an overview of all the dimensions and sub-dimensions, whereas the next sections show the detailed description of all of them.

[4] The term “actor” here includes type of device, component and application

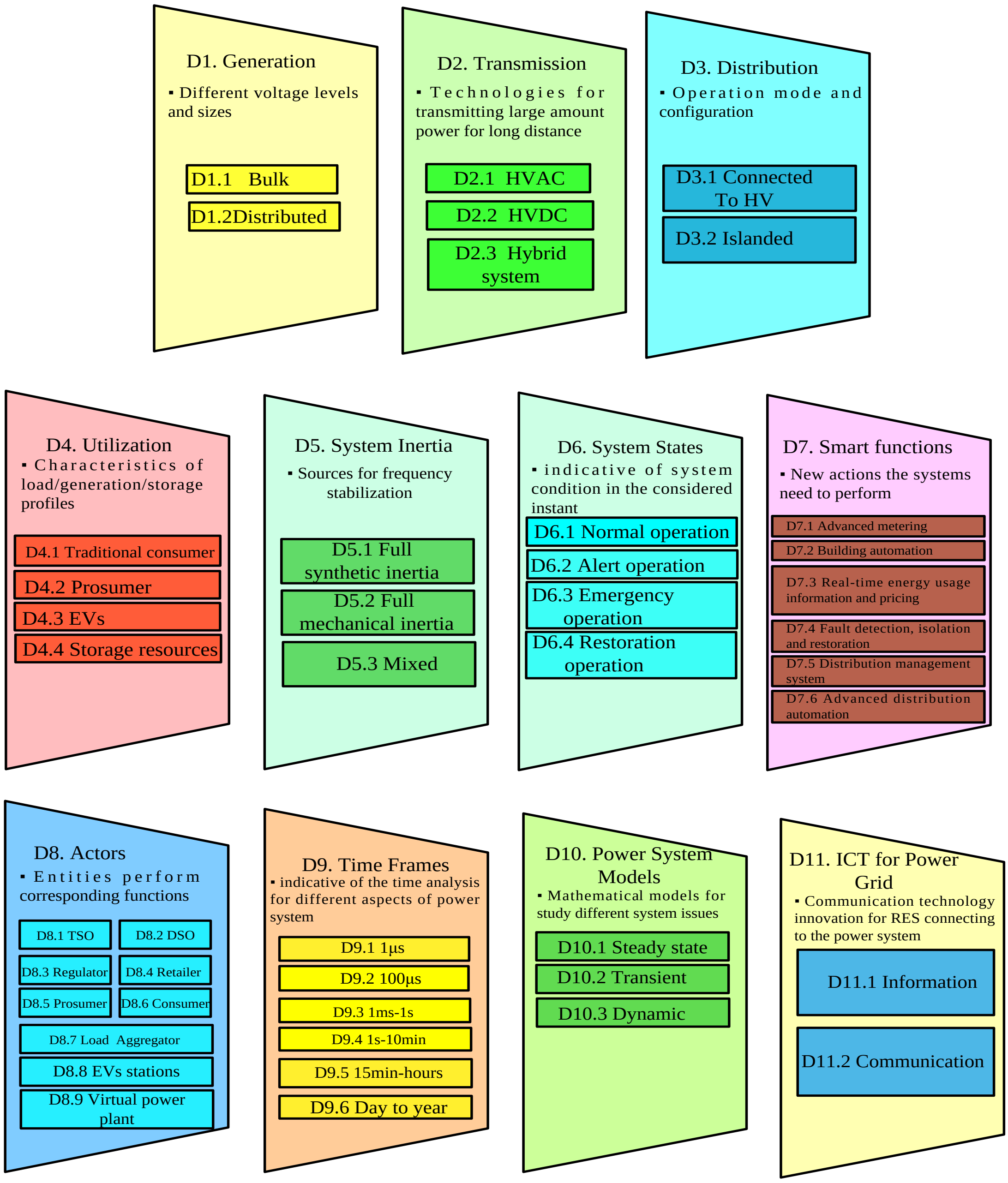


Figure 32 Dimension of the Framework

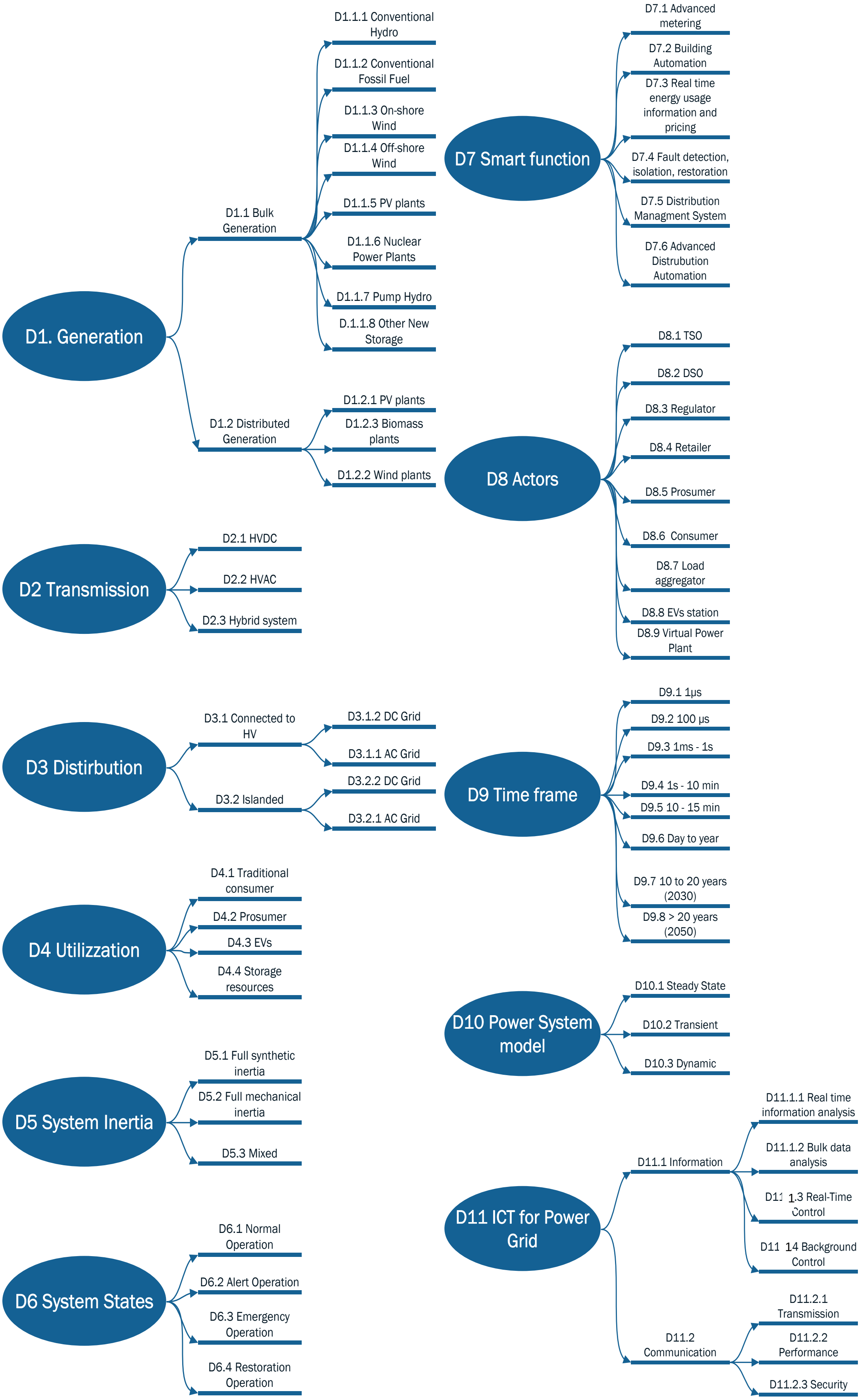


Figure 33 Dimensions and sub-dimensions of the Framework

7.1 Dimension definition

7.1.1 D1. Generation

The term *generation* indicates the production of electricity. This can happen in big plants connected to the High Voltage Transmission system and referred as ***Bulk Generation*** or in Medium-Low Voltage Distribution Grid as ***Distributed Generation.***

A special category are ***storage facilities***. These are special technologies able to store electric energy in some other form (chemical energy, potential energy, kinetic energy etc.) and then are able to come back to electricity, when needed. Every storage technology is characterized by a certain efficiency, a Power/Energy rating, a time deployment and other technological and investment characteristics, which will address its use and remark its sustainability into the grid. The most interesting technologies are: pumped hydro (the only one which is connected nowadays to the grid), CAES (Compressed Air Energy System), Batteries, Flywheels, Supercapacitors. They will play a pivotal role in the future Energy Grid. Difference between Bulk Generation Storage and Distributed Generation Storage is that Bulk Storage is meant to be a large-scale storage, whereas distributed is much smaller.

This dimension lists a certain number of generation technologies, which potentially can be connected to the future grid. Table 10 provides some specifications on particular sub-dimensions:

Table 10: D1 selected sub-dimensions details

Conventional Hydro	All the Hydro sources connected to High Voltage Transmission making use of Pelton, Francis and Kaplan hydro turbines with medium to high Rated Nominal Power. In Europe potential for this kind of plants is almost exhausted: only space for mini and micro hydro applications is left.
Conventional Fossil Fuels generators	Steam Power Plant, Combined Cycles and Turbo Gas plant.
Biomass	As Distributed Energy Sources, except for Wind and PV applications, biomass is very well distributed throughout all Europe unlike other renewable sources like geothermal and marine energy. Biomass however are also exploited to produce gas other than only electric energy.

At this stage it is important to classify RES according to two their connection to the grid and their dispatchability. In general, RES-based plants can be connected to the grid either by a conventional turbine - synchronous machine system (hence, they add rotating inertia to the grid), or by power electronic converters in grid-tied mode (reproducing the frequency of the grid), without adding inertia. Furthermore, the primary source of the RES-based plant (and consequently its power production) can be stochastic or dispatchable. In the first case, primary sources like wind or sun are time-variant and are not controllable.
In the latter case, the primary energy is controllable (e.g., pumped hydro power plants) and therefore the production can be completely decided in advance.

Table 11 shows the most important technologies together with their classification (red: not present; green: present).

Table 11: RES classification

	Rotating Inertia	Dispatchability
Photovoltaic Panels		
Wind turbines		
Conventional Hydro plants		
Biomass plants		
Geothermal plants		

7.1.2 D2 Transmission

This dimensions focuses on the nature of the transmission grid and its basic architecture. With the third energy package, the process of a unique pan-European Market is under implementation. A pan-European transmission grid can help this process, by connecting regions characterized by high demand, with region characterized by an excess of generation. The enhancement of the transmission of electricity between countries and the assurance of the connection of dispersed renewable generation (like off-shore wind) will be implemented by constructing new overhead lines.

In general, there is a low public acceptance related to the construction of traditional overhead lines; however, forcing TSOs to use other options (such as underground cables or HVDC links), will increase the design and the operation of the pan-European system [96], even if HVDC can become an economical way to transport large amount of energy over long distances.

A focus on HVDC potentiality in balancing the grid is needed, if these systems will be massively used in the future.

7.1.3 D3 Distribution

The DS is the interface connecting most part of the costumers with the High Voltage Transmission grid and therefore to Bulk Generation. Furthermore, it is where DERs are mainly connected to the grid. The voltage levels are lower than the ones used for the transmission system. The structure of the network is weakly-meshed, and it is usually operated in radial way.

The basic architectures options here refer to the possibility to operate the DS with AC (Alternating Current) or DC (Direct Current) architecture. The operations can be managed in a connected way with the transmission grid, with possibility either islanding in case of big contingencies, or operating directly in islanding by covering consumption with DER.

7.1.4 D4 Utilization

This dimension refers to the consumption side of the electric grid. In the traditional passive network, consumers change the load in a stochastic way. Nowadays, distributed energy storage (coupled to a customer or stand-alone), automation and new types of customers are creating a more controllable and responsive demand.

These new users refer to the new figures of ***prosumer***, i.e., a consumer equipped with its own production plant and storage, as well as an automation system, which makes him able to produce its own energy and control in a very fine way its load behavior, potentially been able to furnish ancillary services to the grid.

Then we can also consider **EVs Station** used to recharge electric vehicles, which in the future will more massively enter in the system. The battery inside the single electric vehicles can be used as a storage of energy for the grid. In this way, both the charge of the battery and new services to the grid can be guaranteed.

7.1.5 D5 System Inertia

System Inertia is provided by the kinetic energy of the synchronous generators connected to the grid. Thanks to it, the system can undergo minor unbalances without collapsing. A traditional electric network is a *full mechanical inertia system*.

Mixed case depicts a scenario where the normal inertia provided by synchronous generators will be enhanced by power converters connecting RES[5] and storage system, which will provide the service of virtual inertia (synthetic inertia).

If only power converters are connected through the grid (*full synthetic inertia*), the problem of frequency and inertia changes its nature (as explained in the technical section) and new

5 Note that not all the RES are connected by power converters (e.g., hydro) to the grid, but power converters always interface RES-based plants

structural layout should be used. Frequency nature and its use needs to be redefined, because its value has to be guaranteed by the communication system among the different converters

7.1.6 D6 System States

The states of the system indicate how the system is during the considered instant in terms of operating violations and fulfillment of its functions. Generally, we can identify five possible states that should be tailored to the various parts of the grid, considering role and relative importance.

1) *Normal* state: all the control variables (system frequency, local voltages levels and transmission power flow) lie within their limits and the reserve requirements are being met;

2) *Alert* state: the control variables are still in the operating ranges, but the reserve requirements are not fulfilled; therefore, in case of occurrence of one fault, the normal state could not be maintained anymore.

3) *Emergency* state: the system state is outside from the normal operating ranges; the inequality constraints are not verified (for example, a line is overloaded).

4) *Extremis* state: the system is no longer working, and thus both inequality and equality constraints are not verified (because the balance between input and output)

5) *Restoration* state: the system is operated for allowing the restarting after a black out.

7.1.7 D7 Smart Functions

Smart function refers to the new actions that the future grid needs to obtain an optimal management and operation of the system, even in the presence of high RES penetration. Being these new solutions still not implemented on a big scale, there exist a lot of classification and terminology changing as state of art evolves. In this list only functions linked with distribution and utilizzation part of the grid were added because they are more focused on the scope of the project. However, as seen from chapter 3, new functions at the transmission level also exist and could be considered in our system.

D7.1 Advanced Metering – Advanced metering infrastructure (AMI) is an integrated system of smart meters, communications networks, and data management systems that enables two-way communication between utilities and customers [91].

D7.2 Building Automation – The term Building Automation Control System indicates the measuring, interlocking, closed loop control and supervisory technology for technical building services [92].

D7.3 Real time energy usage and pricing – The focus is on the analysis and use of real-data from the perspective of the prosumer and their corresponding impact on network operations.

D7.4 Fault Detection, Isolation and Restoration – Every DSO should improve its capability to detect faults, inslanding and reconnetting the islanded portion of the network to the main grid in case of important contingiencies, for restoring its service and help the global grid restoration.

D7.5 Distribution Management System – The Distribution Management System represents a suite of application software that monitors and controls the distribution system equipment based on computeraided applications, market information, and operator control decisions [93].

D7.6 Advanced Distribution Automation – The Advanced Distribution Automation is a Smart Grid technology that can be implemented on the electric grid’s distribution system of local power lines and neighborhood substations. It often offers the greatest bang for the buck. It improves reliability with real-time monitoring and intelligent control [94].

7.1.8 D8 Actors

The actors involved in the electricity systems are:

- DSO
- TSO
- Regulator
- Retailer
- Consumer
- Generation Units
- Dispatchable Units
- Non-dispatchable Units
- Prosumer
- Load aggregator
- EV station
- VPP
- BRP

Chapter 3 shows the detailed description of all of them.

7.1.9 D9 Time Frame

The dimension time frame is indicative of the analysis of different aspects of the power system operation [97]. The time frames are needed to identify the usual time length of the phenomena we want to study, i.e., to understand minimum time step for our simulations tools or recording frequency for our measurement instruments. Our models complexity and level of detail will depend on the time frames of interest.

D9.1 ≈1 µs - Requested for studying fast voltage variation caused by lightning and for online wideband grid impedance identification (for voltage stability purposes).

D9.2 ≈100 µs - Requested for studying switching over-voltages.

D9.3 1ms÷1s - Requested for studying the variation dynamic of the system, included the fast primary control intervention and frequency containment.

D9.4 1s÷10min - Requested to characterize very precisely the behavior of the non-dispatchable units. This data is not always available. With this time step it is possible to study the dynamic of the secondary control (related to the frequency) and control action on power generators (e.g., output variation).

D9.5 15min÷hours - requested to characterize most of the loads and the generation units for quasi-steady state studies, and the tertiary regulation.

D9.6 day÷years - requested for studying optimal operation on the system (e.g., dispatching and losses minimization).

7.1.10 D10 Power System Model

A model is a set of algebraic/differential equation describing the dynamics of all the variables of our system. The power system is a complex system; therefore, same elements can be represented with different set of equations giving rise to different behavior for the variables of the system. Furthermore, the variables of the system can change depending on the level of complexity of the model. Depending on (i) the time-frame, (ii) the system status and (iii) other requirements in the type of analysis we want to perform, the model can be precise tailored on our application. In general, we can refer to three families of models:

D10.1 Steady State - Most of the time the electric grid can be approximately considered operating in steady-state (also called in quasi steady state) because dynamic variations of variables are very small and an algebraic model can capture fundamental phenomena in the grid [53].

D10.2 Transient State – With the term transient, here we refer to the study of the system or component behavior under very fast electro-magnetic changes or during big contingencies causing very fast changes in the variables of the system.

D10.3 Dynamic State - It refers to the dynamics of variables during operation of the grid considering electro-mechanical phenomena happening to the machines under no or small contingencies.

7.1.11 D11 ICT for Power System

The purpose of this section is to offer an insight on the information and telecommunication architecture requirements that would enable 100% RES. As highlighted in the requirements for D6, D7, D9, and D10 it is clear that accuracy in data transfer, and data processing abilities are key aspects to be considered. Also, measured data sources must be handled in both slow-changing and fast-changing environments. By considering other possibilities, the ICT layer for power systems can also be highly abstracted in the following ways:

D11.1[6] Requirements for RES
D11.1.1 Data Analysis
 D11.1.1.1 Real time information
 D11.1.1.2 Bulk (non real-time) data
 D11.1.1.3 Data Size and Model
 D11.1.1.4 Algorithmic Simulation
D11.1.2 Data Control
 D11.1.2.1 Real-Time Control
 D11.1.2.2 Background Control
 D11.1.2.3 Policy Control
 D11.1.2.4 Security
D11.2 Communication infrastructure
 D11.2.1 Components
 D11.2.2 Protocols
 D11.2.3 Performance
 D11.2.4 Security
 D11.2.5 Technology Enablers for 5G based ICT

Therefore, the following definitions are given by considering both possible ICT structures presented in Figure 33 and the above listed (red-highlighted) alternatives.

D11.1 Information requirement for RES Power systems: With the advent of advanced metering infrastructure, readings can be taken frequent intervals, and for example readings taken every 5, 10 or 15 minutes, can see a dramatic increase in the level of data collected in the order of terabytes to exabytes. Data sets that are terabytes to exabytes in size and coming from a range of different sources is starting to be the norm.

D11.1.1.1 Real time information analysis: It is clear from the requirements set forth in D7 that there will be time frames measured in the nano-seconds and therefore the information system for 100% RES must be able to capture and route monitored information in the same time scale.

D11.1.1.2 Bulk (non-real time) data monitoring: The information system of 100% RES will not be one big monolith system, but instead must be an efficient system for gathering relevant data like asset management information, operation management information, pricing details for demand response, and forecasting information for renewable energy. The transfer of this type of information would be seen as non-real time, as in data captured in 30 minute intervals and transferred in bulk once a day to the information system for 100% RES.

D11.1.3 (D11.1.2.1) Real-Time Control: Given the need to maintain and even improve system reliability and resiliency, ensuring safety and security, and maximizing operational

[6] Red highlighted parts are foreseeable alternatives for replacing the same sub-dimensions or new additions. They will be used in the following deliverables for the ICT layers.

efficiency in 100% RES when it is in a Dynamic State, it will be important that real-time control is supported by the information system used in 100% RES. This will require management and control decision making to be performed closer to the edge of the network, to the point of enabling autonomic control behavior.

D11.1. 4 (D11.1.2.2) Background Control.

D11.1.1.3 Data Size and Model: While storage sizes of terabytes to exabytes have already been mentioned, it is worth noting that the information system for 100% RES must support the capture of raw data and cleansed data. Doing this in an information architecture that supports “Data Lakes”, and then taken into a standardized data model representation (CIM) will greatly assist the data analysis processing that will take place after the monitoring data is captured.

D11.1.1.4 Algorithmic Simulation: With monitored data collected the information system of 100% RES should allow access to developers of algorithms that would support 100% RES to observe the “smartness” of their algorithms in action and to record, recall and learn from such simulations in a mirrored environment that does not intrude on the live monitored data.

D11.1.2 Data Control Requirements for RES Power systems: Having captured the monitoring data, and having performed simulated trials of frequency and voltage control techniques on historical data, the algorithms behind those techniques need to be deployed in the field and run live in a 100% RES grid network. In order to do this the information system for 100% RES must be able to control the relevant network elements in their steady, transient and dynamic state.

D11.1.2.3 Policy Control: A policy-based information system is one based on combination of rules and services where rules define the criteria for resource control and is a management paradigm that separates the rules governing the behavior of a system from its functionality. Each policy rule is composed of a set of conditions and a corresponding set of actions. The condition defines when the policy rule is applicable. Once a policy rule is activated, one or more actions contained by that policy rule may be executed. A policy-based system is the main way for controlling many forms of large-scale, adaptive systems that dynamically change their behavior in response to changes in the environment, such as the case with 100% RES networks. Such dynamic adaptability is fundamentally important in controlling and managing the increasingly complex systems that will make up 100% RES network and especially to control the relevant network elements in their steady and/or transient state.

D11.1.2.4 Security: No discussion of information systems would be complete without setting requirements on security, especially given the cyber hackers now have the capability and the intent to destroy hardware and data and the potential to disrupt utility operations. Even the slightest change in the data being received or sent to network elements could affect the stability of the grid and even jeopardize human safety. Information systems that are required to have encryption technologies, vulnerability scanning, data leak protection, and persistent security monitoring is a must. Also given that extensive data on consumer energy usage will be collected, from a privacy perspective it will be critically important to guard data in a controlled manner.

D11.2 Communication Infrastructure - This project proposes a complete ICT solution for energy systems with 100% renewable energy sources, including Mobile Networks based on Long Term Evolution (LTE) and 5G standards, as well as future concepts such as advanced Iota and machine-to-machine communication. This project will show that this approach is a highly successful solution for supporting remote automation tasks in next generation energy systems, providing optimal performance through very low latencies, high data throughput and quality of service differentiation using the latest and planned 3GPP standards. This will ensure the best possible system security and maximum reliability for the energy systems. See Chapter 6 for more details.

D11.2. Components: The communication systems will use 5G mobile network technology, including evolved LTE standards as well as multi-RAT (Radio Access Technologies) networks, combining LTE and new radio technologies. Key technology components include extensions to new spectrum such as higher frequency bands, access and backhaul integration to non-3GPP radio standards, optimized device-to-device communication, flexible spectrum usage, multi-antenna transmission, ultra-lean design, and full separation of user and control layers. See Chapter 6.1 for more details.

D11.2.2 Protocols: To ensure scalability, security, and mobility, IP and non-IP Iota shall be able to communicate though the 5G network. See Chapter 6 for more details.

D11.2.5 Technology Enablers for 5G based ICT: The following technologies will enable this project to utilize 5G as a communication technology for RE-SERVE solution: Network Slicing, Software-Defined Networking, Network Function Virtualization, new Radio Technology, enhanced Device-to-Device communication and better energy efficiency. See Chapter 6.2.1 for more details.

11.2.1 *Transmission.*

11.2.2 *Performance:* to enable connectivity for a very wide range of applications with new characteristics and requirements, the capabilities of 5G wireless access must extend far beyond those of previous generations of mobile communication. These capabilities will include greatly enhanced system capacity, very high data rates everywhere, very low latency, ultra-high reliability and availability, support for low-cost devices and minimal energy consumption, and energy-efficient networks, and will fully meet the requirements for the RE-SERVE solution. See Chapter 6.2 for more details.

11.2.3 Security: Mobile telecommunications networks traditionally offer very high security standards: Functions such as Authentication, Network Surveillance, Ciphering and Data encryption belong to standard mobile functions and are well suited for the RE-SERVE solution. See Chapter 6 for more details.

7.2 Analysis of RES penetration in the Smart Grid Architecture Model (SGAM)

This chapter gives eventually the mapping of the use cases based on the previous identified scenarios (dimensions), study focus, roles, ICT architectures, etc. to the SGAM framework. It also includes introduction to SGAM, how to conceptually mapping the dimensions, making the use cases.

7.2.1 SGAM concept and objectives

Motivation

Hundreds of standards are required to improve efficiency and effectiveness of smart grids. However, we are still in the early stages of developing framework for the standards, and we need to have a means to assess limitations, commonalities, and problems of various standards. From the other side, there are also a lot of different architectures; we need to find a unified model covering and comparing them all. Taken decisions during the development process of an infrastructure should be also documented and represented in a unified standard fashion. In order to shift existing paradigms to Smart Grids systematically, we need to have an architectural overview of Smart grids to reuse the assets as much as possible. This would enable gaps identification in the development of future systems.

Concept

Smart Grid Architecture Model (SGAM) provides support for use case design in the context of smart grids with an architecture approach in which interoperability of different layers are well represented in a technology neutral manner for both existing and future power systems.

Application

One of the main application areas of SGAM is in use case mapping. Having a use case with sufficient information considering different interoperability layers, SGAM provides the basis to map it on a three-dimensional representation merging the dimension of domains (covering the complete electrical energy conversion chain), zones (representing the hierarchical levels of power system management), and interoperability layers.

Different architecture designs can be compared thanks to such representations. This would support gaps identification in Smart Grids standardization, and migration scenarios to improve existing/installed architecture.

SGAM can be also used for work coordinating between different technical committees (TCs) and stakeholders, business models investigations, developing interface specifications, identifying new applications and services, mapping prosumers and competitors, etc.

7.2.2 SGAM Structure

SGAM is a three-dimensional model that is merging the dimension of 5 interoperability layers including component, communication, information, function and business, with the 2 dimensions of the Smart Grids Plain consists of zones and domains. Zones represent the hierarchical levels of power system management including power system equipment and energy conversion called process, and information management consist of field, station, operation, enterprise, and market. Domains cover the complete electrical energy conversion chain from bulk generation, transmission, and distribution, to Distributed Energy Resources and customer premises.

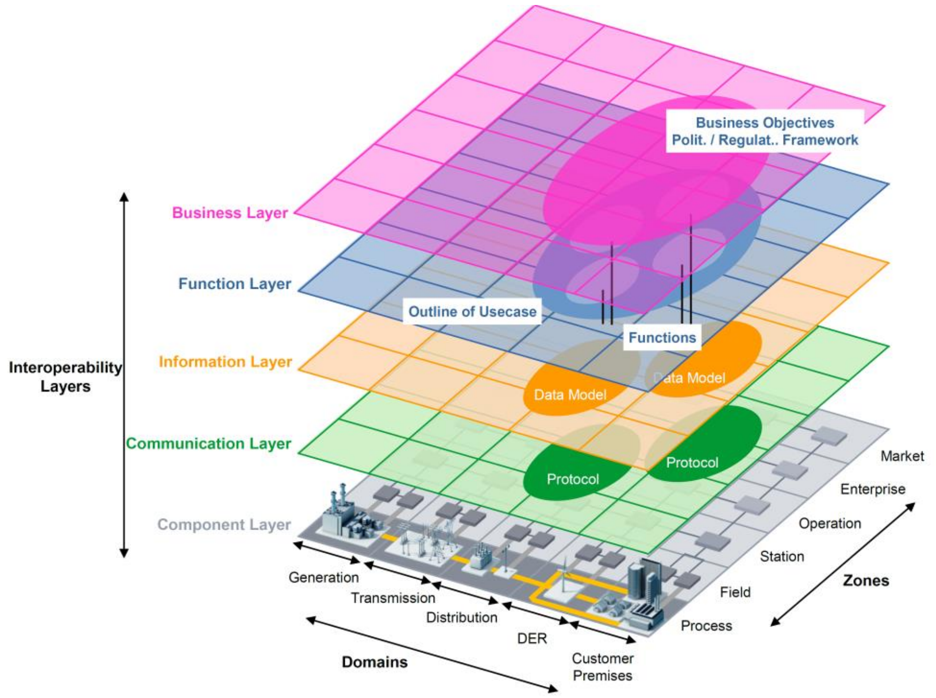


Figure 34 Smart Grid Architecture Model (SGAM) - Source: CEN-CENELEC-ETSI Smart Grid Coordination Group

SGAM hierarchical zones

Process. Process covers all types of energy transformations including the physical equipment which are directly involved. Equipment examples in the process zone are generators, transformers, transmission lines and cables, circuit breakers, electrical loads, and any kind of sensors and actuators, etc.

Field. Protection, control, and monitoring equipment of the power system process are all considered in field zone. Any kind of intelligent electronic devices which acquire and use process data from the power system, protection relays, and bay controllers are some examples of the field components.

Station. The areal aggregation level for field components falls in station zone. Station includes substation automation, local SCADA systems, data concentration, plant supervision, etc.

Operation. Systems which are actually hosting power system operation are considered in operation zone. Some examples of operation systems in different domains: Energy Management Systems (EMS) in generation and transmission systems, Distribution Management Systems (DMS), Virtual power plant management systems (aggregating several DER), Electric vehicle (EV) charging management systems in customer premises.

Enterprise. Management entities, commercial and organizational processes, services and infrastructures for enterprises (utilities, service providers, energy traders, etc.) are considered in the enterprise zone. Some examples are staff training, customer relation management, asset management, billing and procurement, logistics, etc.

Market. Energy trading and all possible market operations as either mass or retail market are put in the market zone.

SGAM Domains

Bulk generation. It includes all types of electricity production in bulk quantities, such as hydro power plants, fossil and nuclear power plants, off-shore wind farms, large scale solar power plant, etc.

Transmission. Infrastructure and organization which are in charge of electricity transportation over long distances.

Distribution. Infrastructure and organization which distributes electricity to customers.

Distributed Energy Resources (DER). DERs are small-scale power generation which are directly connected to the public distribution grid with typical production in the range of 3 kW to 10 MW.

Customer Premises. Hosting prosumers including industrial, commercial, and residential facilities. Prosumers can be either pure consumers or producers such as micro turbines, photovoltaic generation, etc. Electric vehicles storage and batteries are also hosted in this domain.

Interoperability among system

Smart Grid Architecture Model (SGAM) is formed by putting 5 interoperability layers together on the Smart grid plane basis including domains and hierarchical zones. **Figure 35 Interoperability Layers** represents these 5 interoperability layers between 2 systems A and B. Interoperability is defined as the ability of two or more devices from the same vendor, or different vendors, to exchange information and use that information for correct cooperation. In simple words, different layers are to answer to the following questions:

What business processes and regulatory constraints apply?

What functions are required?

What data should be exchanged?

How should the information be exchanged?

What physical elements are required?

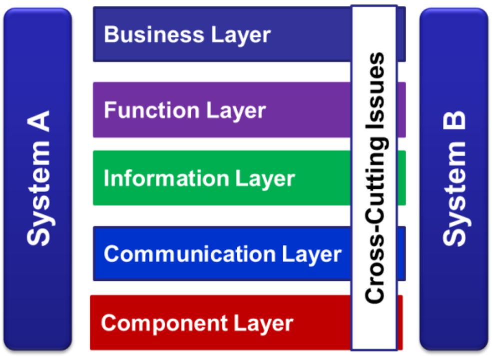


Figure 35 Interoperability Layers

Component layer. The physical distribution of all participating components in the smart grid context, including system actors, applications, power system equipment, protection and tele-control devices, communication network infrastructure and any kind of computers.

Communication layer. In this layer, data exchange procedure, technologies, protocols and standards are described for the specific use case, functions, and information objects.

Information layer. This layer represent messages, measurements, alarms, and in general all data and information which are exchanged between actors of component layer and function layer. It includes information objects and considered canonical data models which ease communication between different data formats.

Function layer. It includes functions along with their relationships from an architectural viewpoint. The functions are independent from actors and physical implementations in applications, systems and components.

Business layer. The business layer represents the business view on the information exchange related to smart grids. It supports business executives in decision making related to business models and specific business projects (business case) as well as regulators in defining new market models.

7.2.3 Mapping RE-SERVE dimensions into SGAM

As a first attempt, we can map our sub-dimensions to the SGAM axes, to better categorize and classify the various items. This operation can be helpful afterwards in the project for the definition and the construction of the SGAM model of our Use Cases.

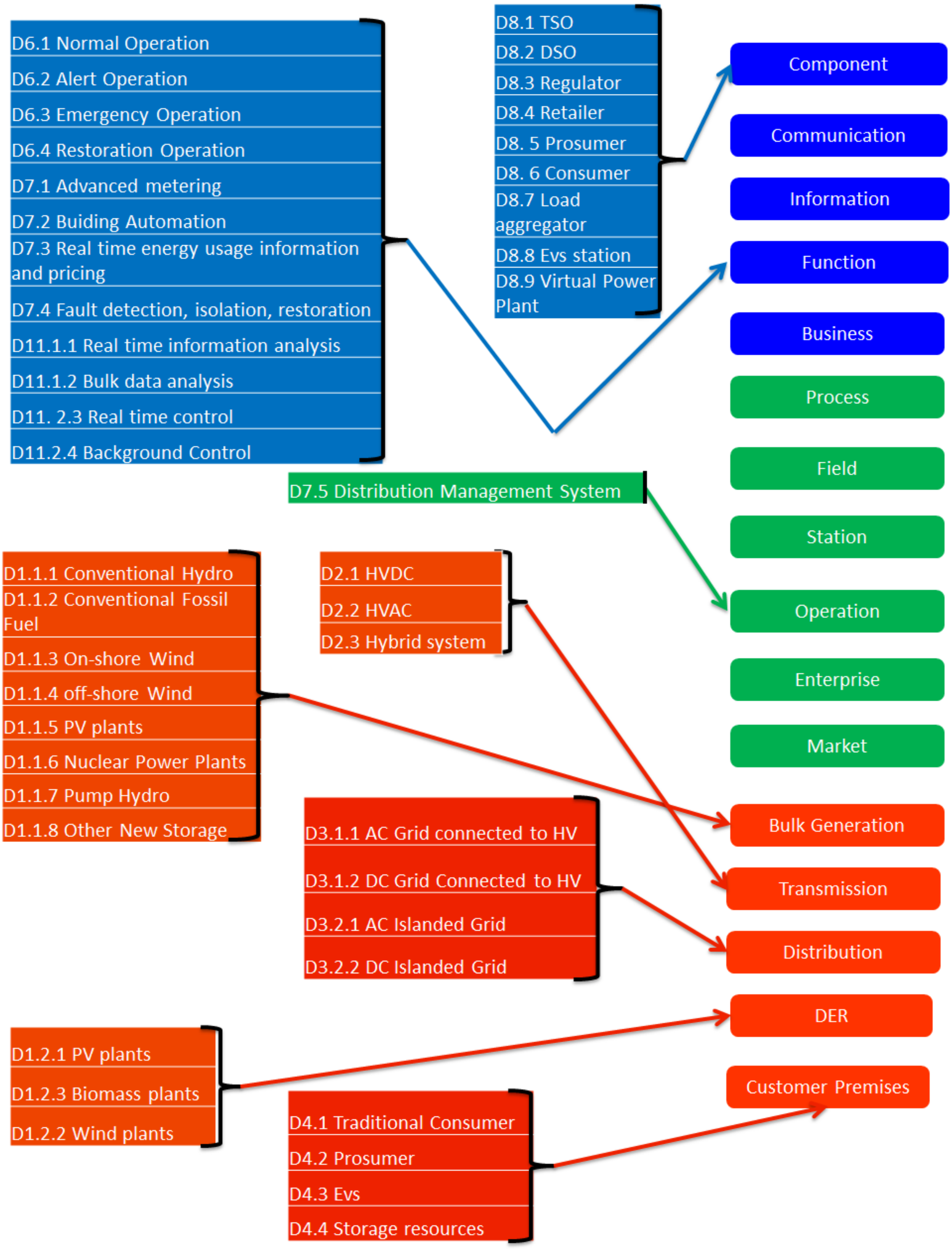


Figure 36 Dimensions mapping to the SGAM

8. Scenario Identification

Starting from the whole set of dimensions and sub-dimensions of the previous chapter, Scenarios are build up on selecting the appropriate dimensions and sub-dimensions described in the previous chapter. The last section presents the procedure for incorporating the defined scenarios into the SGAM framework.

8.1 Objective

In this chapter, we build the high-level scenarios and describe them. These scenarios need to be:

- *Reasonable* with respect to expected evolution of energy systems (for which we highlighted the most important elements in the first part of the document, i.e., chapter 2 to chapter 6).
- *Well defined* in terms of crucial elements of the power system and information and communication systems.
- *Useful* for designing, later, specific use cases to be used to simulate and test proposed approaches for managing grids up to 100% RES penetration grids.
- *In harmony* with the two main research questions of the project, i.e. frequency and voltage stability tailored on the national context and test-bed of Romania and Ireland.

8.2 Scenario definition

We can define a Scenario as a collection of various elements identifying a unique set of assumptions for the study. In particular, we need to identify a high-level description on four key groups:

1. Sub-scope of the analysis (starting from the general research questions scope, e.g., what aspect of voltage and frequency stability we want to assess).
2. Information of the system (generation mix, general architecture and presence of particular components in the future grid relevant to that particular sub-scope etc.).
3. Emerging (Smart) functions, including the requirement of ICT technologies, infrastructure and functions.
4. Main involved actors.

We address these key groups by dividing them in the 11 dimensions to point out the most important high-level *characteristics* and *technological* choices at our disposal, considering also the *objective* of the scenarios identification (refer to the section 8.1). Each key group can comprehend one or more dimensions. Groups can be seen in Figure 37:

1. System info (D1, D2, D3, D4) where we gather all dimensions about basic physical components of our system
2. Sub-scope of the analysis (D6, D9, D10) where we focus on the particular aspects of the research question we want to analyze, clearing out some general details about the analysis and simulation we want to perform in the future on our system.
3. Emerging Functions (D5, D7, and D11) gather new smart functions and ICT services need in our system. D5 can be ambiguous in the sense that mechanical inertia is not a function but a physical characteristic of our system

while synthetic inertia, although an essential one, it's a service provided by converters in high RES grid. To highlight this last feature we put this information in Emerging Function group.

4. Actors (D8) lists principal actors involved in grid use and management.

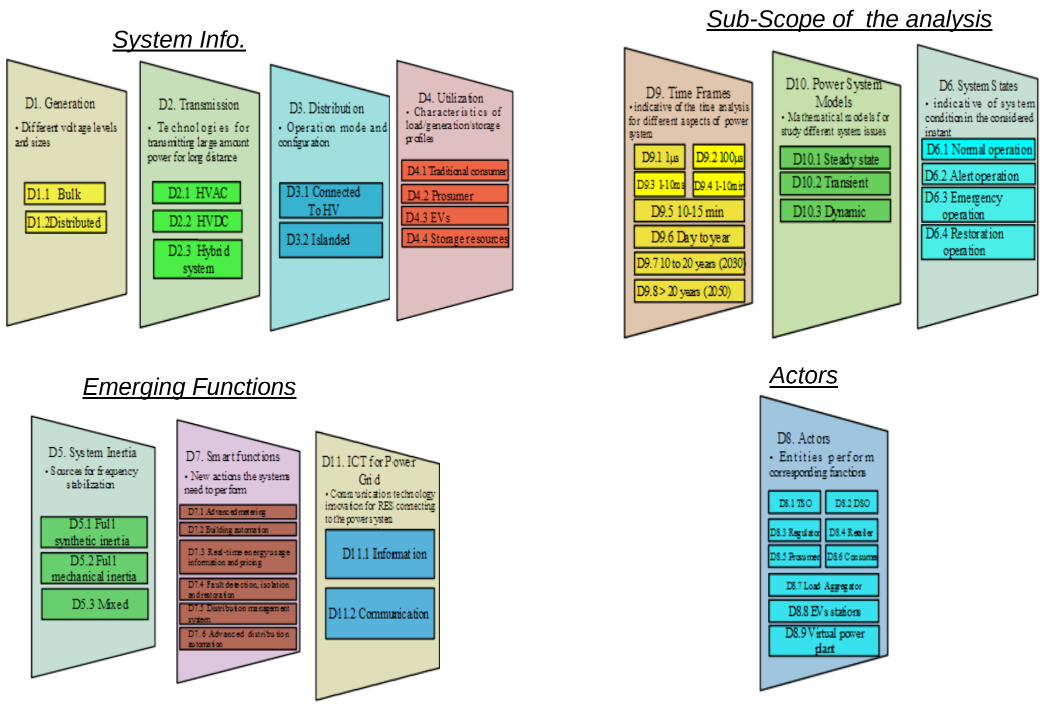


Figure 37: Groups division of the dimensions

We define scenarios by selecting the proper subset of dimensions to study. Every scenario is then refined by adding a qualitative description of system and analysis characteristics. Several scenarios were proposed to fully describe and address the two research questions.

First we present scenarios for the frequency stability study and then for the voltage issue.

8.3 Scenarios for research question on frequency in Romanian context

8.3.1 Synoptic View of the Scenarios

The proposed scenarios are divided in two groups. Each group shares an equal general view and many similarities between the singular scenarios.
The scenarios are presented in a synthetic manner in Table 11.

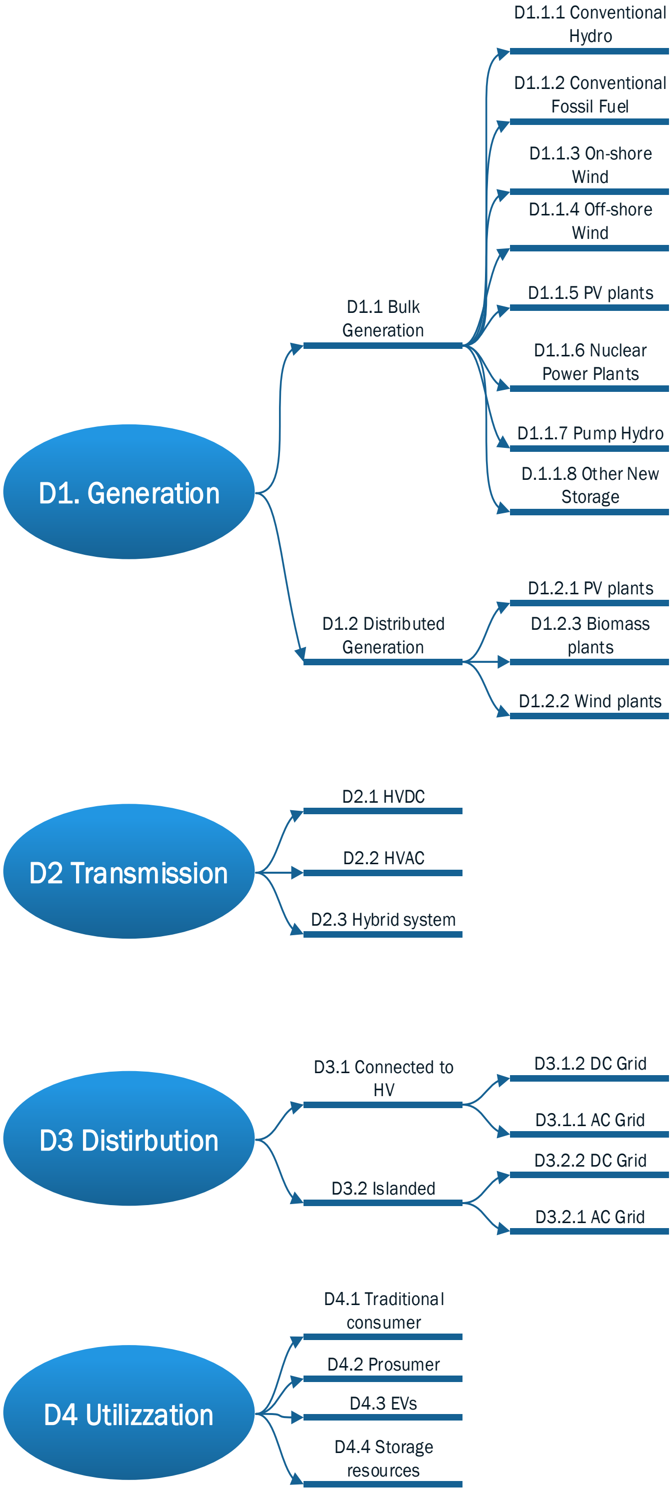
Table 12: frequency scenarios synoptic view

Group	Code	Title	Description
	Sf_A1	Mid term probable, still fossil	This scenario considers a 100%RES but with still CO_2 generation parts.
	Sf_A2	100%RES mostly wind	In this scenario, the main focus is to simulate 100% RES in normal condition considering that wind generation and

Sf_A			bulk storage will be mostly developed also considering HVDC connection and a medium level of prosumers into the grid.
	Sf_A3	100% RES mostly PV	In this scenario, main focus is to simulate 100% RES in normal condition considering that PV generation and distributed storage (batteries) will be mostly developed, also considering HVDC connection and a significant level of electrical vehicles including V2G.
Sf_B	Sf_B4	100% RES, fully synthetic inertia for frequency stability studies	Main focus on simulation of 100% RES in normal operation as well as alert and emergency situations when wind, solar and storage are the solely primary source of power generation. Bulk generation, such as wind farms, is connected to the transmission level whereas distributed generation is connected to the distribution system.
	Sf_B5	100% RES, mixed inertia for frequency stability studies	Main focus on simulation of 100% RES in normal operation as well as alert and emergency situations when wind, solar and storage are added to the conventional sources of power such as hydro and pump hydro power plants. Bulk generation, such as hydro power plants, is connected to the transmission level whereas distributed generation is connected to the distribution system.

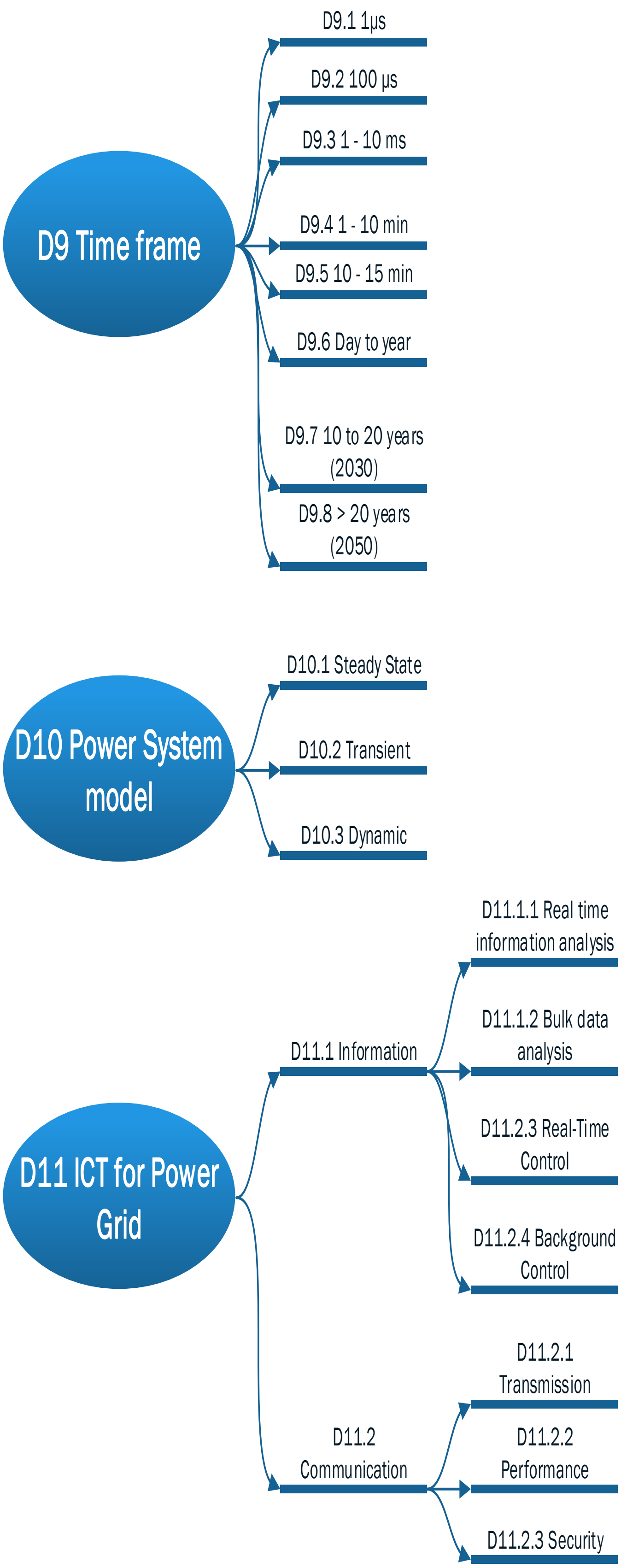
These scenarios are only hypothetical considered for the purpose of the Project and are not subject of National Strategy or Program or any other type of assumptions.

Synoptic view of the scenarios we chosen with sub-dimensions is shown in Figure 39.



Frequency Stability In Romanian Contest				
Sf_1	Sf_2	Sf_3	Sf_4	Sf_5
X	X	X		X
X				
X	X	X	X	X
	X	X	X	X
X	X	X	X	X
X				
X	X	X		X
			X	X
X	X	X	X	X
X	X	X	X	X
X	X	X	X	X
	X			
X	X	X	X	X
			X	X
X	X	X	X	X
			X	X
X	X	X		
X	X	X	X	X
	X	X		
X	X	X		

		Frequency Stability In Romanian Contest				
		Sf_1	Sf_2	Sf_3	Sf_4	Sf_5
D5 System Inertia	D5.1 Full synthetic inertia				X	
	D5.2 Full mechanical inertia					
	D5.3 Mixed	X	X	X		X
D6 System States	D6.1 Normal Operation	X	X	X	X	X
	D6.2 Alert Operation	X	X	X	X	X
	D6.3 Emergency Operation	X	X	X	X	X
	D6.4 Restoration Operation					
D7 Smart function	D7.1 Advanced metering	X	X	X		
	D7.2 Building Automation	X	X	X		
	D7.3 Real time energy usage information and pricing		X	X		
	D7.4 Fault detection, isolation, restoration	X	X	X		
	D7.5 Distribution Managment System	X	X	X	X	X
	D7.6 Advanced Distrubution Automation	X	X	X	X	X
D8 Actors	D8.1 TSO	X	X	X	X	X
	D8.2 DSO	X	X	X	X	X
	D8.3 Regulator	X	X	X		
	D8.4 Retailer	X	X	X		
	D8.5 Prosumer	X	X	X	X	X
	D8.6 Consumer	X	X	X		
	D8.7 Load aggregator		X	X		
	D8.8 EVs station		X	X		
	D8.9 Virtual Power Plant	X	X	X	X	X



Frequency Stability In Romanian Contest				
Sf_1	Sf_2	Sf_3	Sf_4	Sf_5
X	X	X	X	X
X	X	X	X	X
X				
	X	X		
X	X	X	X	X
			X	X
X	X	X	X	X
			X	X
X	X	X		
X	X	X	X	X
X	X	X		

Figure 38: frequency scenarios with associated sub-dimensions

8.3.2 Detailed view of the scenario group Sai

The construction of the scenarios for the Romanian power system considers energy potential, geographical position and national medium/long term strategy.

The scenarios consider two steps:

a) the first step refers to a medium term horizon that assumes a mix of generation from classical power plants, but excluding coal-fired power plants;
b) The second step refers to a long term horizon, with a mix of generation originating 100% from renewable sources. This scenario will consider two different shares of energy from wind and solar plants.

In terms of Power ratings, the scenarios will start from the expected average load. The share of generation will then consider the potential of hydro generation, the evolution of wind and solar projects and the lifetime of other generation sources (i.e., nuclear and natural gas).

Scenario 1 (Sf_1) is partly RES (not 100%) and considers the long term exploitation of the nuclear and fossil based generation. The increase in the share of generation from wind and solar is assumed based on the actual conditions. Scenarios 2 and 3 (Sf_2 and Sf_3) are considering 100% RES and are built on different meteorological approach like: mostly wind generation (Sf_2) and mostly PV generation (Sf_3). Scenario 2 is focused on larger wind evolution of generation. Scenario 3 considers the situation of higher solar penetration - based also on technological advancements on PV segment, in the situation of some limitations in developing the segment of wind generation. The generation from biomass is maintained constant because there are no clear data about the potential in the future.

The scenarios proposed for Romania are correlated with the expected average share of generation from the various sources that can be estimated at the present time. The required installed capacity in all types of generation sources is an estimation based on two factors: the share of each technology in generation and the capacity factor of each technology.

The actual average capacity factor C_F for wind turbines (C_{F_WND}) is 27%, for solar (C_{F_PV}) is 14%, while for hydro is (C_{F_HYD}) 28%. It is important to notice that this 28% for hydro is an average, because actually some hydro power plants can reach up to 80% while other ones only 10%. There is not enough information to assume an increased capacity factor for wind. On the contrary, the technology for PV panels can improve until the time of the assumed scenarios, thereby increased capacity factor up to 16% will be considered. The capacity factor for hydro power plants in Romania was established based on statistical data. It will be considered unchanged taking into account that the installed power in new hydro units will not change too much.

Table 13 shows the expected share of power generation from the various target sources and the corresponding power, calculated in such way to meet the average power demand. The evolution of power demand in Romania will depend on economic growth factors, but also on the strategy for energy efficiency. Although the economy would increase, based on the statistical data, it is assumed that the average consumption will be increasing in tight range.

Table 13: share of yearly average generation assumed for the three scenarios for Romania

	Scenario 1		Scenario 2		Scenario 3	
	Share	Gen	Share	Gen	Share	Gen
	%	MW	%	MW	%	MW
Wind	26.5%	1776	49.0%	3283	30.0%	2100
Solar	11.0%	737	20.0%	1340	40.3%	2821
Fossil	15.0%	911	0.0%	0	0.0%	-

Nuclear	18.0%	1300	0.0%	0	0.0%	-
Biomass	1.0%	67	1.0%	67	1.0%	70
Bulk storage	0.0%	-	0.0%	-	0.0%	-
Distributed storage	0.0%	-	0.0%	-	0.0%	-
Hydro	28.5%	1910	30.0%	2010	28.7%	2009
Load	100.0%	6700	100.0%	6700	100.0%	7000

The average production for each type of generation is used then as an input for deducting the necessary installed capacity of this specific type of production (P_{INST}). As an example, for P_{AVRG_WND} = 1776 MW yearly average power of wind generation over the year – for scenario 1, the necessary wind capacity is:

$$P_{INST\_WND} = P_{AVRG\_WND} / C_{F\_WND} = 1776 / 0.27 = 6578 \text{ MW (approximated to 6600 MW)}$$

Which is more than double than the existing installed capacity of 2979 MW in wind at the end of the year 2015. A complete assumption of the necessary installed capacities is provided in Table 14.

Table 14: proposed installed capacities, P_{INST}, for the three scenarios for Romania

	Scenario 1	Scenario 2	Scenario 3
	MW	MW	MW
Wind	6600	12000	7800
Solar	5300	8400	18000
Fossil	12000	-	-
Nuclear	1400	-	-
Bio	70	70	70
Bulk storage	1000	1500	1500
Distributed storage	500	2500	4500
Hydro	6800	7200	7200
Total	33570	31670	39070

Storage has been considered as having no influence on the one-year time frame production or consumption portfolio, as it is expected that there is symmetry in consumption (storing the energy) and production (releasing the stored energy). At this stage the efficiency of storage cycles is not considered. However, in future analysis this will be detailed based on the storage technology (with focus on pump storage and battery storage).

With the average use of each technology and after getting the needed installed capacity, we can use existing daily / weekly / monthly wind and solar profiles to infer the power system evolution in the new mix of produced energies and of storage means, thus being able to better identify critical situations for system stability analysis in the situation of high RES penetration.

8.3.3 Sf_A1: Midterm probable (close to zero carbon emissions)

8.3.3.1 General description/introduction

Scenario 1 is partly RES (not 100%) and considers the long term exploitation of the nuclear and fossil based generation.

Expansion of renewables depends on three factors: the potential of primary resource, the legislation, and the technology evolution. Romania has a good potential for solar energy in south of the country, for both small size panels installed on buildings and large power plants installed in the distribution networks. In regards to the wind resource, there is room for more on-shore power plants to be connected to the transmission network, particularly concentrated in Dobrogea, Banat and Moldova.

8.3.3.2 First group of Dimensions: System Information (D1, D2, D3, D4)

The hydraulic potential in Romania includes both rivers and lakes, with more power potential in run-of-river power plants. The existing installed hydro power generation, is about 6700 MW. Very small distributed hydro generators are also in place. The share of generation from hydro power plants ranges from 20% to 34% of the total generation, depending on the hydraulic energy and the energy export. Based on the actual information, the installed power will increase in small amount.

There are two nuclear power units operating in Romania, with 700 MW installed each. These units are used to generate energy at the base load. The share of generation from nuclear sources is about 17%-19% of the total generation.

Romania owns important reserves of natural gas. An 800 MW combined cycle power plant was recently commissioned in Romania, and similar facility of 400 MW is about to be constructed. Other projects could be commissioned following the new resources discovered in the Black-Sea. It is expected that high efficiency natural gas based generators will be used in Romania.
For the above-presented reasons, this scenario includes also non-renewable sources and it is not 100%RES.

The structure of the generation would be according to the table below:

Table 15: generation mix of Sf_A1

	Scenario 1
	MW
Wind	6600
Solar	5300
Fossil	12000
Nuclear	1400
Bio	70
Bulk storage	1000
Distributed storage	500
Hydro	6800
Total	33570

Currently, there is no HVDC link in Romania. In order to integrate more renewable sources, Transelectrica has planned the construction of several HVAC lines, especially from Dobrogea, the region with the best wind energy potential. No HVDC projects at this scenario.

In Romania there is no important islanded system that may require attention for frequency regulation procedures. There would be islanding issue and distribution grid is considered as classical AC.

Romania is about to adopt new legislation that allows the increase in the efficient use of energy, namely by introducing the prosumer as a network user. Although this is possible, taking into consideration the economic situation in Romania, the PV panels will be installed if the technology price will drop in terms of cost effectiveness. The storage systems could be adopted, but at small scale. At this stage, however, the electrical vehicles are not adopted at large scale.

8.3.3.3 Second group of Dimensions: Sub-scope of the analysis (D6, D9, D10)

D6. As the frequency control requires availability of power reserved, the following situations can be met:

- Normal Operation – there is appropriate active power reserve for frequency control

- Alert Operation – the generation from wind and solar resources reaches very high levels
- Emergency Operation – an important regulation power plant is unavailable

D9&D10. The frequency in a power system is mainly a global parameter. From frequency point of view, all network elements are interconnected and synchronized, which means that any action taken in a single point of the network will affect the entire network.

Frequency is a parameter that requires a 24-hour planning and intervention of energy resources in the active powers balancing. As stated in Section 4.3.2, the specific time frame for fastest intervention of an energy source to provide frequency control starts from 1 second and is required to be maintained up to 15 minutes. The deployment time for the next control levels are thus higher. Any reaction beyond 15 minutes is more economic than technical.

Therefore, a dynamic model is only requited for simulation. A time frame below 1 second is usually necessary for frequency measurement, calculation, and equipment reaction. Load flow calculation can be required in order to check the network security for reserve availability in case of contingency.

8.3.3.4 Third group of Dimensions: Emerging Functions (D5, D7, D11)

D5. According to the generation mix we can see that we would have both classical generators (hydro, thermal, nuclear) and also Power Electronics based (wind and PV). Therefore, we have considered mixed inertia (mechanical and synthetic provided by converters)

D7&D11. The smart grid operation is ensured by the three vertical layers in Figure 39: Energy Metering Layer, including smart metering, Advanced Instrumentation Layer (PMUs, microPMUs, high reporting rate measurements, high accuracy and bandwidth of instrument transformers) and Information and Communication Technology Layer will be used to ensure data, transfer and processing the data between all actors involved in the smart grid. The Energy Metering involves those data necessary for business development, the advanced instrumentation ensures the extraction of the necessary data for developing the new strategies for technical services, while the ICT is the backbone of the smart grid operation.

The technological advancement in renewable energy sources, as a sub-concept of smart grids, will be linked to other technologies that are/will deployed at all levels of the electrical network. They will include advanced metering, building automation, distribution management system, and advanced distribution automation. The new concepts of prosumer and virtual power plant are possible by advanced ICT and automation systems at the user level.

The actual technology is not allowing real time energy usage information and pricing, and therefore we did not consider at this stage. This function will be available in the smart home concept, which also requires fast internet connection and affordable home automation technology.

8.3.3.5 Actors (D8)

The right hand side of Figure 39 illustrates the main actors involved in the future business architecture of the Romanian power system. They are standardized in various commercial or technical codes. The TSO and DSO are the main actors in the electrical network administration, the retailer will facilitate the logistic deployment of low level applications such as the prosumer, the virtual power plant, and demand response at the classical consumer. Load aggregation is highly dependent on the ICT technology and is less probable that it will be available at the time frame for which the scenario 1 is defined.

A scheme of the future Romanian power system is illustrated in Figure 39, where the various regulatory, business and technical layers are represented by horizontal planes. The link between them is ensured by the vertically represented layers.

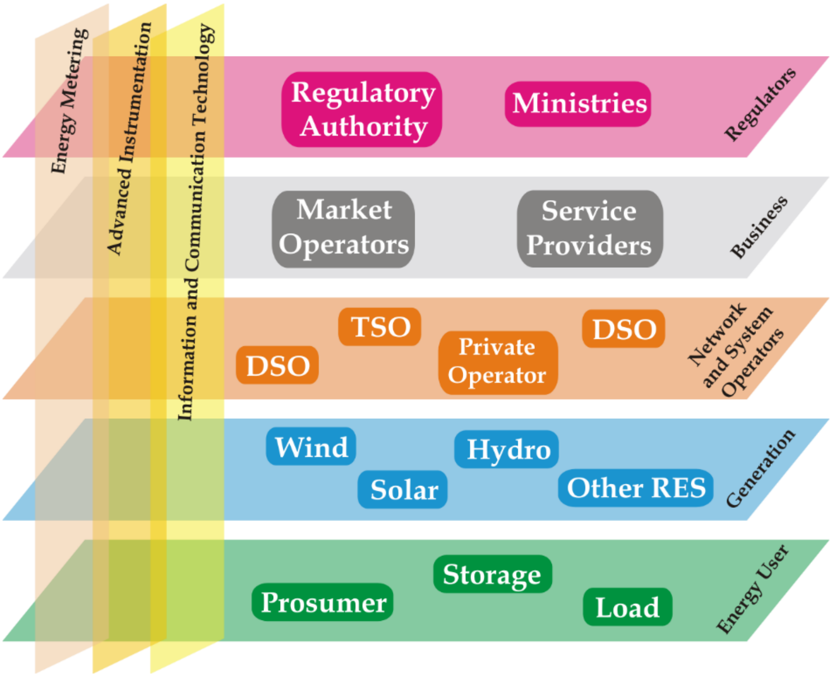


Figure 39: Main features of Romanian System

The Energy User Layer and the Generation Layer are at the bottom of the smart grid architecture since they are the basic source of interaction for the envisaged analyses of frequency and voltage control. The Energy User Layer includes the classical load as well as the newly created prosumer and storage. The storage entity is also part of the Generation Level as the energy extracted in the Energy User Layer is provided back to the network in the Generation Layer.

The Network and System Operators Layer consists of all types of operators. A particular case of operator is the private operator, which is required to provide technical services, such as the RES operator of the VPP operator.

All entities involved in trading energy are connected to the Business Layer. The technical services are subjected to power market contractions. The Market Operators, which are the controllers of the Business Layer, are administrating the various forms of the power market. The two market operators are OPCOM – that administrates the Day Ahead Market and the Centralized Market for Electricity Bilateral Contract, and the Balancing Market Operator – a function ensured by the Romanian TSO.

The Regulatory Layer is at the top of the Model, which includes the Romanian Energy Regulatory Authority and the Ministries of Resort (Ministry of Energy and Ministry of Economy). The Business Layer is governed by decision taken within the Regulators Layer.

8.3.4 Sf_A2: 100% renewable energy, mostly wind

8.3.4.1 General description/introduction

Scenario 2 is RES 100% and considers the long term evolution of RES as mostly developed on wind generation.

The main differences with respect to the first scenario are due to the absence of nuclear and fossil plants. Consequently, the installed capacity in fossil and nuclear is zero.

Further on, will be described only those dimensions that are different to Scenario 1.

8.3.4.2 First group of Dimensions: System Information (D1,D2,D3,D4)

Wind generation and solar generation increased compared to first scenario. Accent is considered on wind.

The structure of the generation would be according below table:

Table 16: generation mix of Sf_A2

	Scenario 2
	MW
Wind	12000
Solar	8400
Fossil	-
Nuclear	-
Bio	70
Bulk storage	1500
Distributed storage	2500
Hydro	7200
Total	31670

In order to integrate more renewable sources, that are mostly feasible in a concentrated area, a HVDC link is considered to evacuate power. That is another difference compared to Scenario 1.

The storage systems are considered to be adopted, in medium scale and mostly on transmission grid. Also, the electrical vehicles will be adopted at moderate scale and possible V2G.

8.3.4.3 Other Dimensions

Other dimensions are equal to Scenario Sf_1 except for:

D7. We consider also the appearance of Real time energy usage information and pricing as end users are going to look more and more after cost savings.

D8. We find one modification compared to Scenario Sf_1 as "Load aggregators" will be in place to manage balancing in better shape.

D9. We consider that time horizon for this scenario is longer going in the area of more than 25 years for D9.8.

8.3.5 Sf_A3: 100% renewable energy, mostly solar

8.3.5.1 General description/introduction

Scenario 3 is also RES 100% and considers the long term evolution of RES as mostly developed on solar generation.

Hypothesis are very similar to Scenario 2 and therefore the differences with respect to the second scenario are very little. We only present these for Scenario 3.

8.3.5.2 First group of Dimensions: System info. (D1, D2, D3, D4)

Solar generation increased with respect to the second scenario. Also, no fossil and no nuclear generation are present.

The structure of the generation would be according below table:

Table 17 generation mix for Sf_3

	Scenario 3
	MW
Wind	7800
Solar	18000
Fossil	-
Nuclear	-
Bio	70
Bulk storage	1500
Distributed storage	4500
Hydro	7200
Total	39070

In order to integrate more renewable sources distributed in a large area, a HVDC link is not considered to evacuate power. That is a difference compared to Scenario 2.

The storage systems are considered to be adopted, in large scale both in bulk and also in distribution. Also, the electrical vehicles will be adopted at large scale and certainly will include V2G.

8.3.5.3 Other Dimensions

Other dimensions are equal except for:

D8. We find one modification compared to Scenario Sf_1 as “Load aggregators” will be in place to manage balancing in better shape.

8.3.6 Detailed View of the Scenarios group Sf_B (Sf_4 & Sf_5)

The two scenarios of Sf_B will be presented together and differences will be explained within the description.

8.3.6.1 General description/introduction

The incessant integration of offshore wind farms, along with the increasing interest in international power exchange confirms the deployment of DC grids and the transition to future hybrid AC/DC systems. However, to have a smooth and successful transition to future power systems with 100% RES, corresponding sequential solutions and technical advancements are required. Based on this approach, the research work is split in two phases: an intermediate scenario with a mix of mechanical and synthetic inertia, and a long-term scenario with no mechanical inertia and fully synthetic inertia. This is because some countries, like Romania, will retain mechanical inertia provided by hydropower plants while other countries, like Germany, will have almost fully synthetic inertia, which in turn, represents the most challenging scenario.

8.3.6.2 System Information (D1, D2, D3, D4)

Fossil fueled and nuclear power plants are not considered in either scenario since the focus of the project lies on enabling power systems with 100% RES.

Regarding the transmission level, HVAC and hybrid systems are considered. HVDC is excluded since the focus of the studies should be the transformation of the generation and not the network. Hybrid systems are included because offshore wind power maybe only connected via HVDC and hybrid technology could be used to decouple distribution networks and transmission networks as a way of ensuring stability.
Only prosumers are considered on the load side since their load shifting behavior has similar effects as, for example, energy storage in batteries. At this point, we want to simplify the scenario to be able to focus on the challenge posed by low inertia systems.

8.3.6.3 Sub-scope of the analysis (D6, D9, D10)

The operating state of the system considers first the normal operation to calculate and estimate system inertia with the installed generation sources. Then, alert and emergency operation are simulated to test and evaluate system and control capabilities, frequency stability and dynamic performance, considering small and large disturbances.

The time frame of system operation and frequency control is varied in both scenarios. The intermediate scenario will include fast response (non-synchronous) RES, with converters, and slow response Synchronous Generators. Hence, the respective time frame will be in the range of ms-minutes. On the other hand, the final scenario will include only the non-synchronous RES with the time frame lying into ms-second range. Note that the operation time of both slow SG (e.g., with gas or diesel primary energy source) and relatively faster response SG (hydroelectric) is considered.

8.3.6.4 Functions (D5,D7,D11)

D5. As described before, we would like to investigate two different 100% RES scenarios: no mechanical inertia and a mix of mechanical and synthetic inertia. The first scenario assumes that generation units are distributed and connected to the distribution level through power electronics converters. In this case, no mechanical inertia is provided. The second scenario considers a significant amount of bulk generation that provides mechanical inertia alongside the synthetic inertia of distributed generation units.

D7. Since it is assumed that most of the RES are integrated in the distribution level, distribution system operators will have to assume similar responsibilities as transmission system operators. Therefore, a more sophisticated distribution system management and automation system will be required.

D11. Real time information analysis and control are of key importance of for the frequency stability assessment and control.

8.3.6.5 Actors (D8)

In case of 100% RES, virtual power plants can represent groups of distributed generation units that might be used for frequency control purposes. Load shifts by prosumers are another means of ensuring the power balance. TSOs and DSOs may decide to decouple networks so that frequency problems do not affect neighboring networks.

8.4 Scenarios for research question on Voltage in Irish context

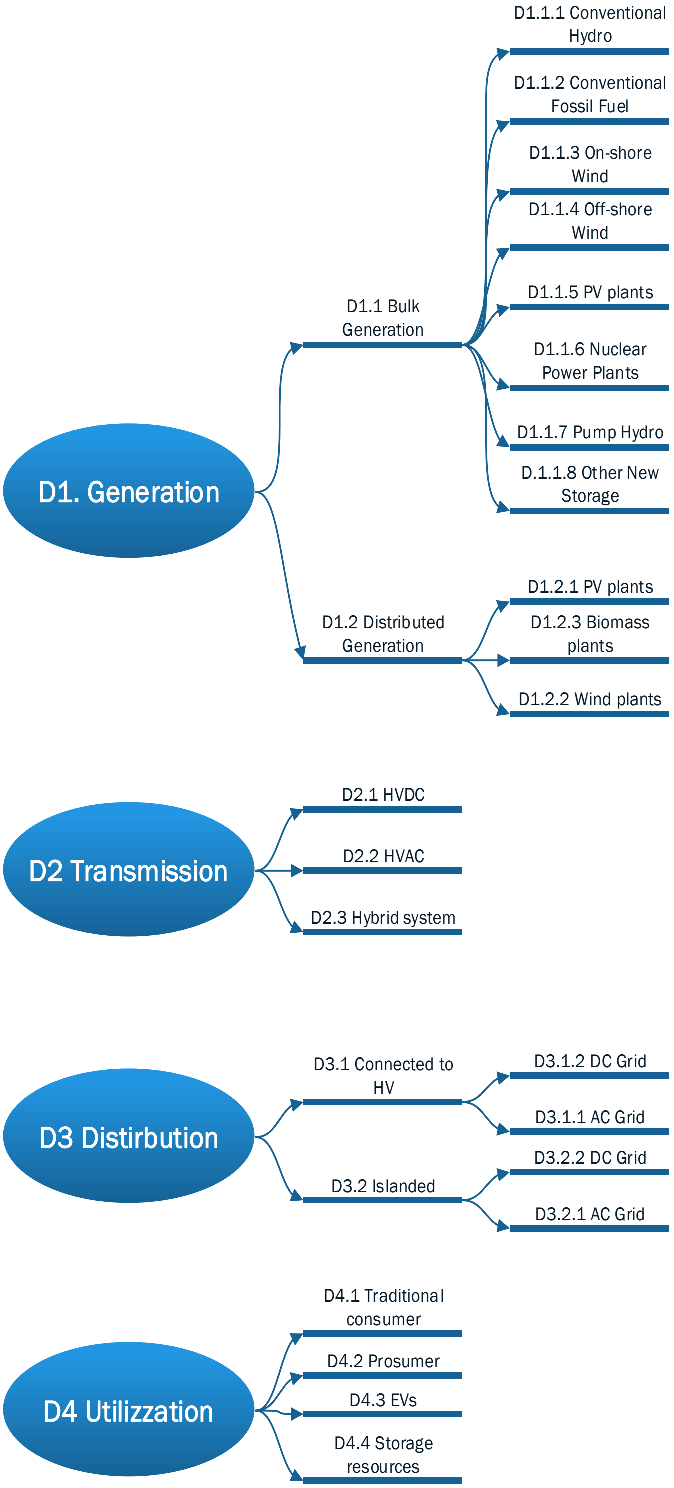
8.4.1 Synoptic View of the Scenarios

The scenarios for the voltage study focus are presented in table below

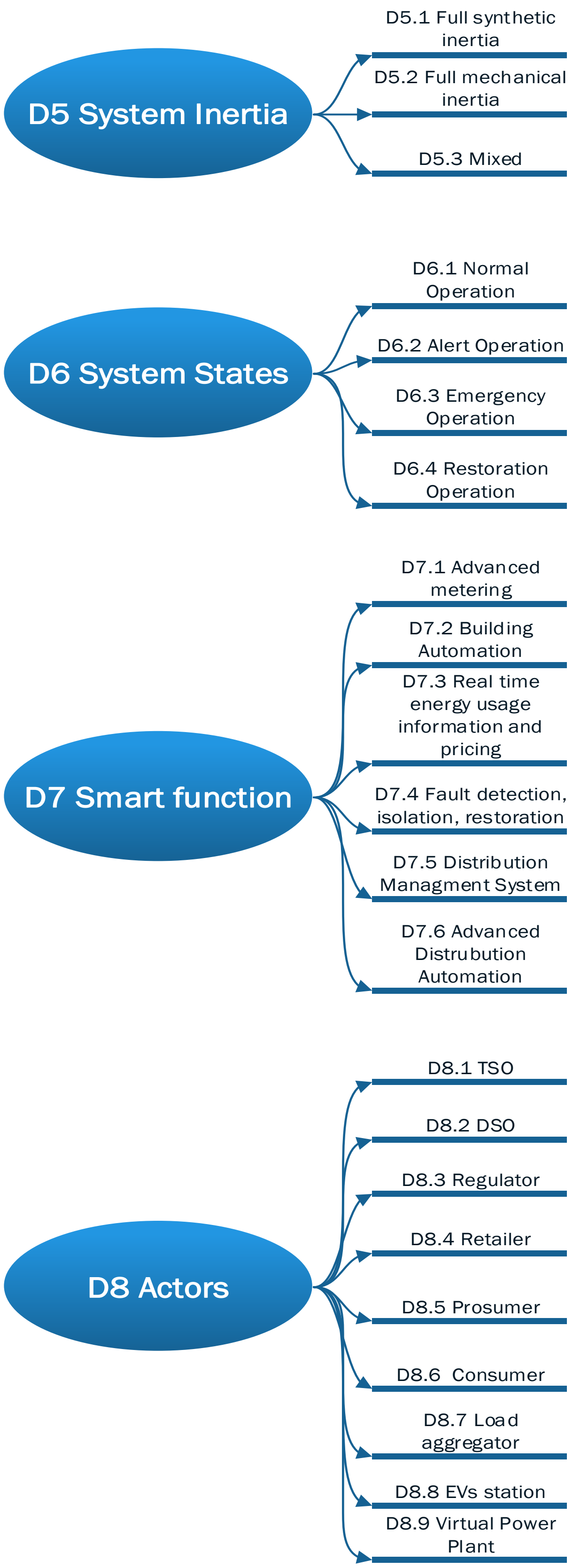
Table 18: voltage scenarios synoptic view

Group	Code	Title	Description
Sv_A	Sv_A1	100% RES (distributed generation and fully synthetic inertia) for voltage stability studies	Main focus on simulation of 100% RES in normal operation when small distributed energy sources such as wind, solar and storage are connected to medium and low voltage feeders. Micro-grid scenario is considered when distributed generation is enough to supply all the loads connected to the feeder.
	Sv_A2	100% RES (distributed generation and	Main focus on simulation of 100% RES in normal operation when small distributed energy sources such as wind, solar and storage are added to the conventional

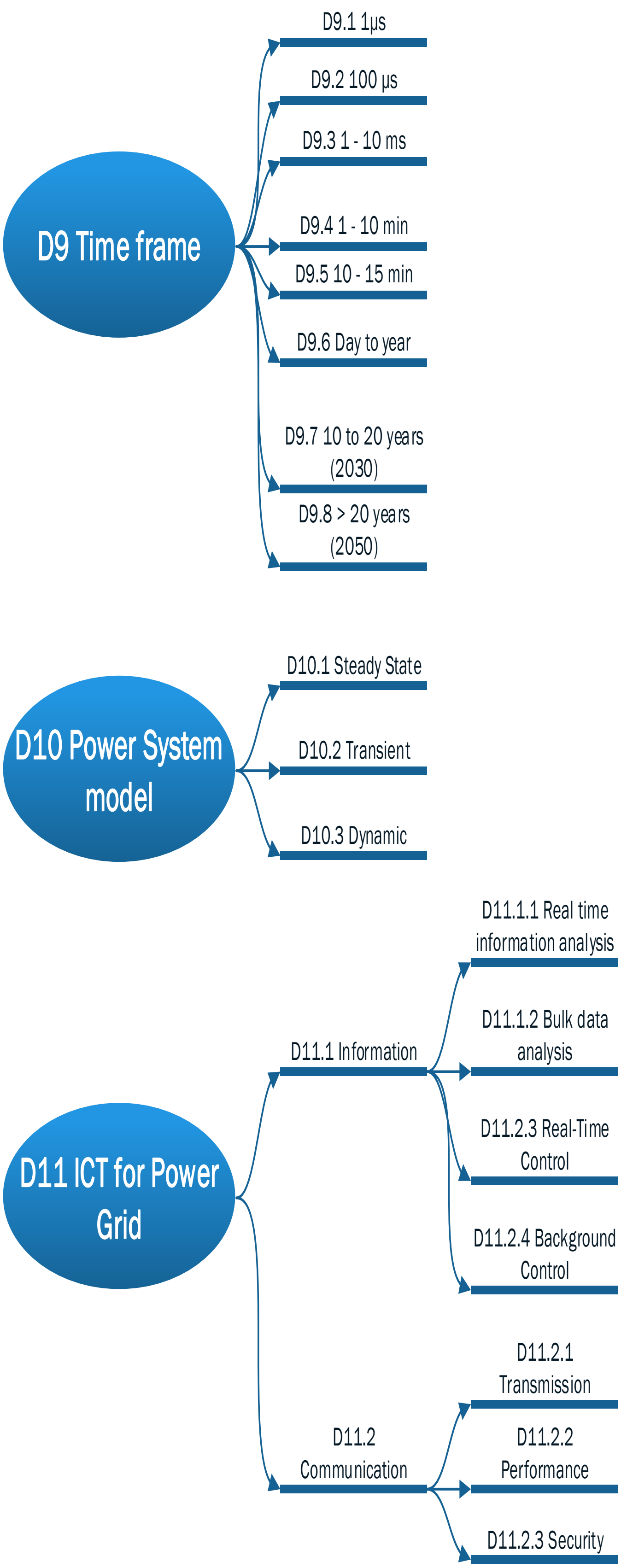
		mixed inertia) for voltage stability studies	sources of power such as hydro and pump hydro power plants. Microgrid gets grid connected when distributed generation is not enough to supply all loads connected to the feeder.



Voltage Scenarios	
Sv_1	Sv_2
	X
X	X
X	X
X	X
	X
X	X
X	X
X	X
X	X
X	X
X	X
X	X
X	X
X	X



	Voltage Scenarios	
	Sv_1	Sv_2
D5.1 Full synthetic inertia	X	
D5.2 Full mechanical inertia		
D5.3 Mixed		X
D6.1 Normal Operation	X	X
D6.2 Alert Operation		
D6.3 Emergency Operation		
D6.4 Restoration Operation		
D7.1 Advanced metering		
D7.2 Building Automation		
D7.3 Real time energy usage information and pricing		
D7.4 Fault detection, isolation, restoration		
D7.5 Distribution Managment System	X	X
D7.6 Advanced Distrubution Automation	X	X
D8.1 TSO	X	X
D8.2 DSO	X	X
D8.3 Regulator		
D8.4 Retailer		
D8.5 Prosumer	X	X
D8.6 Consumer		
D8.7 Load aggregator		
D8.8 EVs station		
D8.9 Virtual Power Plant	X	X



Voltage Scenarios	
Sv_1	Sv_2
X	X
X	X
X	X
X	X
X	X
X	X
X	X

Figure 40: voltage scenarios sub-dimensions

8.4.2 Detailed View of the Scenarios

The two scenarios are very similar and therefore explained together.

8.4.2.1 General description/introduction

The system topology for the voltage stability scenarios are supposed to be the same as for the frequency stability scenarios Sf_4 and Sf_5. Again, there are two scenarios: one without mechanical inertia and another one with mixed mechanical and synthetic inertia. Here the focus of our analysis lies on the distribution level where generating units are mostly interfaced through converters. In the case that no mechanical inertia is provided by synchronous generators (e.g., in the transmission level), generating units are mostly connected to the distribution level. Our research topic will be the interaction of these converters in terms of stability.

8.4.2.2 System Information (D1, D2, D3, D4)

Our choices on the system information remain the same as for the frequency stability scenarios Sf_4 and Sf_5.

8.4.2.3 Sub-scope of the analysis (D6, D9, D10)

Interactions among grid-converters may bring the system into instability. The instability manifests itself as a harmonic oscillation on the top of the AC voltage and it is intended in the small-signal sense. This may already happen during normal operation. Restoration operation may be considered with the meaning that the converter-level controllers can be tuned in such a way to restore the desired stability margins by using the concept of Virtual Output Impedance. For voltage profile regulation, the considered system state is normal operation as well. Restoration may be considered when proper actions are taken to restore the voltage profile within the limits.

Steady state is important for both small-signal voltage stability and voltage profile regulation. Dynamic models, for instance averaged and switch-mode models, are fundamental for small-signal voltage stability study. Transient models are relevant for voltage profile regulation.

To capture up to kHz with the Wideband System Identification (WSI) method, time frames down to micro seconds are required. To perform, instead, voltage profile regulation along a feeder, ms up to 10 minutes time frames are needed.

8.4.2.4 Emerging Functions (D5, D7, D11)

D5. For the system inertia holds the same characteristics detailed in Sf_4 and Sf_5.

D7.The WSI technique is used as advanced metering tool to identify key interface impedances within the system so that stability margins can be calculated in nearly real time.

A distribution management system (most likely located at substation level) will collect all the identified impedances and calculates the stability margins. Based on the nearly real time stability analysis, the implemented algorithm will derive an impedance profile the grid-connected converter should exhibit so that the system voltage stability is maintained with sufficient stability margins. To enable the smart function described above, an advanced distribution automation will include a communication infrastructure between the substation and the grid-connected converter controllers. For voltage profile regulation, the smart function under consideration is an optimized demand response algorithm that uses historical data, again located at the substation level.

D11. Real time information analysis and control are of key importance of both small-signal voltage stability and voltage profile regulation to keep tracking of the fast changes.

8.4.2.5 Involved Actors (D8)

The DSO will manage the above mentioned smart functions. In the scenario, prosumers are envisioned to be connected to the grid via power electronics converters. This means that not only the sources, but also the loads are connected to the grid via power electronics converters. They both participate to the online impedance identification, monitor of stability margins, and stability improvement via virtual impedance concept. The same actors are considered for voltage profile regulation.

9. Conclusions and next steps

The increase in the exploitation of RES for electricity generation in a time frame up to 2050 is widely reported in all the perspective analyses of the energy sector. However, there is no universal consensus on the share of RES that will be reached. It may range from 20 to 70 %. Nevertheless scenarios with 100% of RES has been considered and are highly attractive for the zeroing of environmental impacts.

From this perspective it seems worth to study those scenarios in which the production of electricity from RES poses considerable technical challenges in terms of frequency and voltage control. New techniques and strategies need to be devised and tested.

The implementation of proper control strategies needs adequate fast information exchange among various generators and converters that requires enhanced data communication infrastructure. The next generation, available in the next few years, of 5G mobile communication systems is a candidate for playing this role.

With reference to Romania and Ireland where we will fit the testing and demonstration of the designed frequency and voltage control strategies, we proposed 7 different scenarios on which we will base the specification of use-cases for simulation purposes. Although 100% RES penetration scenarios does not look that likely at 2050, they have been considered along with scenarios characterized by a lower RES penetration and different mix of RES in terms of wind and PV power.

The next steps of the WP will be focused on the identification of uses cases to be applied in WP4 and WP5, for testing the frequency control strategy (designed in WP2), and voltage, control strategy (designed in WP3).

The use-case will be identified starting from the 7 scenarios proposed in the deliverable, through a SGAM approach. The detailed mapping will be presented in the next two deliverables of the WP1 with reference to the development of a Business layer, Component layer, Information layer, and Communication layer.

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List of Abbreviations

B2B	Business to Business
BMS	Building management system
CAPEX	CAPital Expenditure
CCS	Carbon Capture and Storage
CENELEC	European Committee for Electro technical Standardization
CEP	Complex Event Processing
COTS	Commercial off-the-shelf
CPMS	Charge Point Management System
CSA	Cloud Security Alliance
EMS	Decentralised energy management system
DER	Distributed Energy Resources
DMS	Distribution Management System
DMTF	Distributed Management Taskforce
DSE	Domain Specific Enabler
DSO	Distribution System Operator
EAC	Exploitation Activities Coordinator
EC	European Commission
ENTSO-E	European Network of Transmission System Operators for Electricity.
ERP	Enterprise Resource Planning
ESB	Electricity Supply Board
ESCO	Energy Service Companies
ESO	European Standardisation Organisations
ETP	European Technology Platform
ETSI	European Telecommunications Standards Institute
EU	European Union
FACT	Flexible AC transmission System
GE	Generic Enabler
HEMS	Home Energy Management System
HV	High Voltage
I2ND	Interfaces to the Network and Devices
ICT	Information and Communication Technology
IEC	International Electro-technical Commission
IoT	Internet of Things
KPI	Key Performance Indicator
LV	Low Voltage
M2M	Machine to Machine
MPLS	Multiprotocol Label Switching
MV	Medium Voltage
NIST	National Institute of Standards and Technology
O&M	Operations and maintenance
OPEX	OPerational EXpenditure
PM	Project Manager
PMT	Project Management Team
PPP	Public Private Partnership
QEG	Quality Evaluation Group
RES	Renewable Energy System
S3C	Service Capacity; Capability; Connectivity
SCADA	Supervisory Control and Data Acquisition
SDH	Synchronous Digital Hierarchy
SDN	Software defined Networks
SDOs	Standards Development Organisations
SET	Strategic Energy Technology
SET	Strategic Energy Technology
SG-CG	Smart Grid Coordination Group
SGSG	Smart Grid Stakeholders Group
SME	Small & Medium Enterprise
SoA	State of the Art
SON	Self Organizing Network

SS	Secondary Substation
TL	Task Leader
TM	Technical Manager\
TSO	Transmission System Operator
VPP	Virtual Power Plant
WP	Work Package
WPL	Work Package Leader
WSI	Wideband System Identification