MARKET ENABLING INTERFACE TO UNLOCK FLEXIBILITY SOLUTIONS FOR COST-EFFECTIVE MANAGEMENT OF SMARTER DISTRIBUTION GRIDS

Deliverable: D1.3

Challenges and opportunities for electricity grids and markets

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 864334

H2020 – LC-ES-1-2019

Document	
D1.3	Challenges and opportunities for electricity grids and markets

Dissemination level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Author(s)	Institution	Contact (*e-mail, phone*)
Matteo Troncia	Comillas	matteo.troncia@iit.comillas.edu
David Ulrich Ziegler	Comillas	david.ziegler@iit.comillas.edu
Tomás Gómez San Román	Comillas	tomas.gomez@iit.comillas.edu
José Pablo Chaves Ávila	Comillas	jose.chaves@iit.comillas.edu
Ellen Beckstedde	Vlerick Business School	ellen.beckstedde@vlerick.com
Leonardo Meeus	Vlerick Business School	leonardo.meeus@vlerick.com
José Villar	INESC TEC	jose.villar@inesctec.pt
André Oliveira	INESC TEC	andre.r.oliveira@inesctec.pt
Bogdan Czarnecki	IEN	b.czarnecki@ien.gda.pl
Rafał Magulski	IEN	r.maguslki@ien.gda.pl
Torsten Knop	EON	torsten.knop@eon.com
Catarina Augusto	E.DSO	catarina.augusto@edsoforsmartgrids.eu
Carla Marin	E.DSO	carla.marin@edsoforsmartgrids.eu
Gonçalo Faria	E-REDES	goncalo.faria@e-redes.pt

Key word	Characterisation of current network regulation and market rules that will shape future markets
Due Delivery Date	2021/07/31
Date of Delivery	2021/07/28

Document version	Date	Change
1.0	2020/10/31	1st draft
2.0	2020/12/15	2nd draft
3.0	2021/01/19	3rd draft
4.0	2021/06/28	4th draft
5.0	2021/07/07	5th draft
6.0	2021/07/14	Final draft
7.0	2021/07/28	Final version

Reviewers		email	Validation date
VITO	Vanschoenwinkel Janka	janka.vanschoenwinkel@vito.be	2021/07/22
UNIMAN	Pierluigi Mancarella	p.mancarella@manchester.ac.uk	2021/07/27

Table of Contents

ABBREVIATIONS.....9

EXECUTIVE SUMMARY.....11

1 INTRODUCTION.....18

2 THE LONG-TERM VISION FOR A CARBON-NEUTRAL EU IN 2050.....22

2.1 EU LONG-TERM VISION AND COMMITMENT TO THE UNFCCC.....22

2.2 NATIONAL ENERGY AND CLIMATE PLANS: BEYOND 2030 UP TO 2050.....24

2.3 DEFINITION OF THE TECHNOLOGY OPTIONS.....25

2.4 TECHNOLOGY OPTIONS AGGREGATION AND CATEGORISATION.....28

2.5 TECHNOLOGICAL OPTIONS IN LONG-TERM EU NATIONAL PLANS.....30

2.5.1 Comparison of long-term ambitions.....31

2.5.2 Technology options considered in the long-term national plans.....32

2.5.2.1 Germany.....32

2.5.2.2 Spain.....34

2.5.2.3 Belgium.....35

2.5.2.4 Portugal.....37

2.5.2.5 Poland.....38

2.5.2.6 Collated list of technology options.....40

3 ANALYSIS OF THE TECHNOLOGY OPTIONS CONSIDERING THE IMPACT ON THE DISTRIBUTION SYSTEM.....43

3.1 LINKAGES AMONG TECHNOLOGY OPTIONS.....43

3.2 SELECTION OF TECHNOLOGY OPTIONS BASED ON THEIR IMPACT ON THE ELECTRICITY DISTRIBUTION SYSTEM (OPERATION AND PLANNING).....47

3.3 FINDINGS OF THE ANALYSIS OF THE TECHNOLOGY OPTIONS.....53

4 FLEXIBILITY NEEDS IN LONG-TERM SCENARIOS.....54

4.1 METHODOLOGY ADOPTED FOR THE LONG-TERM SCENARIO ANALYSIS.....54

4.2 IDENTIFICATION OF RELEVANT SCENARIOS.....56

4.3 ANALYSIS OF THE LONG-TERM SCENARIOS CONSIDERING TECHNOLOGY OPTION DEVELOPMENTS.....62

4.3.1 Description of the scenarios from the technology options.....62

4.3.1.1 Final energy demand.....62

4.3.1.2 Electric power generation.....65

4.3.1.3 Energy storage.....67

4.3.1.4 Buildings – energy efficiency.....68

4.3.1.5 Buildings – electrification of the energy demand.....69

4.3.1.6 Buildings – comparison of the ELEC, H2-P2X, and EE scenarios.....70

4.3.1.7 Transport.....72

4.4 DISCUSSION ON THE LONG-TERM SCENARIO ANALYSIS.....73

4.4.1 The ELEC scenario 73
4.4.2 The H2-P2X scenario 75
4.4.3 The EE scenario 78
4.4.4 Concluding remarks on long-term scenario analysis 80
5 CHALLENGES AND RECOMMENDATIONS CONCERNING THE FUTURE DISTRIBUTION SYSTEM 82
5.1 DISCUSSION ON THE FUTURE DEPLOYMENT OF THE TECHNOLOGY OPTIONS 82
5.2 DISCUSSION ON THE CHALLENGES OF OPERATION AND PLANNING OF FUTURE DISTRIBUTION NETWORKS 85
5.2.1 Long-term DSO operation needs, up and beyond 2030 86
5.2.2 Long-term planning: DSO planning needs, up and beyond 2030 88
5.2.3 Modelling the distribution system: realistic large-scale simulation and planning models 90
5.2.4 Recommendations for long-term planning and operation 90
5.3 DISCUSSION ON THE FLEXIBILITY PROCUREMENT MECHANISMS 91
5.4 DISCUSSION ON REGULATION FOR THE FUTURE DISTRIBUTION SYSTEM 94
5.5 DISCUSSION ON BUSINESS MODELS FOR DSO, AGGREGATORS, AND FSPS 98
6 CONCLUSIONS 104
BIBLIOGRAPHY 110

List of Figures

Figure 1-1. Correlations among EUniversal project tasks 19

Figure 1-2. Structure of the EUniversal Deliverable 1.3 21

Figure 4-1. Methodology proposed for identifying the residual need for flexibility in the distribution system 54

Figure 4-2. Overview of the relationship among the EU COM 773 (2018) scenarios......57

Figure 4-3. Illustrative representation of the selected scenarios 62

Figure 4-4. Changes in sectoral final energy consumption (% change vs 2005)......63

Figure 4-5. Expected final energy consumption for the considered scenarios 63

Figure 4-6. Share of energy carriers in final energy consumption......64

Figure 4-7. Changes in final electricity consumption in 2050 compared to 2015 65

Figure 4-8. Increase in gross electricity generation compared to 2015 65

Figure 4-9. Increase of the total electric power generation capacity (reference 2015)......65

Figure 4-10. Electric power generation capacity by technology expected in 2050 66

Figure 4-11. Newly installed electric power generation capacity for technology, (a) total newly installed capacity per year, (b) share of the newly installed capacity per year for each technology option 67

Figure 4-12. Electricity storage in 2050 (a) total volume of storage, (b) share of storage for different technologies 68

Figure 4-13. Yearly renovation rate of buildings......69

Figure 4-14. Evolution of the energy consumption in buildings in 2050 (compared to 2005) – residential sector......70

Figure 4-15. Evolution of the energy consumption in buildings in 2050 (compared to 2005) – service sector......71

Figure 4-16. Share of electricity in final energy demand buildings 71

Figure 4-17. Share of electricity in space heating in buildings 72

Figure 4-18. Shares in total passengers' cars stock by drivetrain technology 72

Figure 4-19. Shares in total light commercial vehicle stock by drivetrain technology......73

Figure 4-20. Qualitative impact of the scenarios ELEC, H2-P2X, EE considering the deployment of the relevant technology options with respect to the current situation......81

Figure 5-1. Illustration of the approach for quantitatively assessing the flexibility needs in the distribution system 86

Figure 5-2. Illustrative schema of the ongoing evolution of the power system structure......99

List of Tables

Table 2-1. Classification of the technology options 30

Table 2-2. Comparison table of the long-term ambitions of the target countries....31

Table 2-3. Sector legend....32

Table 2-4. Technology options identified for Germany 33

Table 2-5. Technology options identified for Spain....34

Table 2-6. Technology options identified for Belgium 36

Table 2-7. Technology options identified for Portugal....37

Table 2-8. Technology options identified for Poland....39

Table 2-9. Collated list of technology options – Part 1 of 3 - Transport....41

Table 3-1. The five-points scale of the nature and intensity of the linkage between a pair of technology options 43

Table 3-2. Technology options linkage analysis....46

Table 3-3. Overview of the assessment of the impact of technology options on the distribution system – part 1/2....50

Table 3-4. Technology options that impact the distribution system in future scenarios 52

Table 4-1. Approach to estimate the impact of each technology option on the distribution system flexibility needs....56

Table 4-2. Main aspects of the EU Commission COM (2018) 773 scenarios....59

Table 4-3. Main differences among the Category 1 scenarios....61

Table 4-4. Technology options analysis for the ELEC scenario 75

Table 4-5. Technology options analysis for the H2-P2X scenarios 77

Table 4-6. Technology options analysis for the EE scenario....79

Table 5-1. Main challenges and recommendations for the distribution system concerning addressing the future long-term scenarios....85

Table 5-2. Grid DSO needs and respective services....87

Table 5-3. Main challenges and recommendations concerning the operation and planning of the future distribution system 91

Table 5-4. Mechanisms for flexibility procurement Part 1/2. Source: [103] 93

Table 5-5. Main challenges and recommendations concerning the mechanism for procuring flexibility in the future distribution system....94

Table 5-6. Relevant aspects of regulatory sandbox experiences in Europe 97

Table 5-7. Main challenges and recommendations concerning regulation of future distribution system 98

Table 5-8. Main challenges and recommendations concerning the business models of DSOs, aggregators, and FSPs in the future distribution system........ 103

Abbreviations

AMI	Advanced Metering Infrastructure
BECCS	Bio-Energy with Carbon Capture and Storage
BEV	Battery Electric Vehicle
BCR	Brussels Capital Region
CBA	Cost Benefit Analysis
CCS	Carbon Capture and Storage
CEC	Citizen Energy Communities
CHP	Combined Heat & Power
CM	Congestion Management
CoP	Coefficient of Performance
COP21	2015 United Nations Climate Change Conference
CPPS	Cyber-Physical Power Systems
CRE	Commission de régulation de l'énergie
D	Day
DER	Distributed Energy Resource
DG	Distributed Generation
DSO	Distribution System Operator
EC	European Commission
ECV	Electrically Chargeable Vehicle
ETS	Emission Trading System
EU	European Union
EU COM	European Union Commission
EV	Electric Vehicle
FC-EV	Fuel Cell Electric Vehicle
FL	Flanders
FSP	Flexible Service Provider
GHG	Greenhouse Gas
HDV	Heavy-Duty Vehicles
HEV	Hybrid Electric Vehicles
HHP	Hybrid Heat Pump
HP	Heat Pump
HV	High Voltage
ICE	Internal Combustion Engine
ICT	Information and Communication Technology
ISO	Independent System Operator
JRC	Joint Research Centre
LDV	Light-Duty Vehicles
LEC	Local Energy Communities
LV	Low Voltage
M	Month
MCA	Multi Criteria Analysis
MV	Medium Voltage
NECP	National Energy and Climate Plan
NRA	National Regulatory Authorities
OPC UA	Open Platform Communications Unified Architecture

PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicles
P2X	Power-to-X
PV	Photovoltaic
REC	Renewable Energy Communities
RES	Renewable Energy Source
RES-C&H	Renewable Energy Source in the Cooling & Heating sector
RES-E	Renewable Energy Source in the Electricity sector
RES-T	Renewable Energy Source in the Transport sector
RNC2050	Roadmap for Carbon Neutrality 2050
RNM	Reference Network Model
ToU	Time-of-Use
TSO	Transmission System Operator
UMEI	Universal Market Enabling Interface
UNFCCC	United Nations Framework Convention on Climate Change
V2G	Vehicle-to-Grid
W	Wallonia
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
WP	Work Package
Y	Year

Executive summary

The EUniversal project has the primary objective to overcome the existing limitations in the use of flexibility by distribution system operators (DSOs). A Universal Market Enabling Interface (UMEI) will be implemented to foster the provision of flexibility and link the active system management of distribution system operators with electricity markets. In this context, this document analyses the recent and ongoing European policy and strategy that will shape the future electricity grid and markets. Challenges and opportunities for grids and markets are identified and discussed to provide high-level recommendations and contribute to the distribution system evolution.

The ongoing energy transition is already affecting the electricity system; however, given the long-term GHG emission objective to be achieved, fundamental changes are imperative for the distribution system even in the near future. Policy drivers such as the use of renewable sources, the decentralisation of electricity generation, and the electrification of the energy demand will bring fundamental changes to the distribution system. Technology development such as digitalisation allows customers to connect at distribution networks to become active participants who interact with the system. Consumers with distributed energy resources can provide electricity back to the network by installing distributed generation and storage technologies, including electric vehicles. These technologies can provide a wide range of system services (frequency and non-frequency ancillary services, including congestion management) and support grid planning and operation.

The full document provides a high-level assessment of the needs of the future distribution system. This top-down qualitative approach identifies the overall objective to be achieved, the limits of strategies, and the high-level challenges to be addressed. The described top-down approach guides the assessment at the local level (bottom-up approach) that requires local information (e.g., actual deployment of the technology options, technical knowledge of the grid) to determine quantiatively the flexibility needs of a specific distribution network.

As described in this Executive Summary, the EUniversal Deliverable 1.3 contributes to the ongoing transformation of the electricity system by discussing the following points.

- The analysis of the future distribution system by considering the long-term vision of the European Union (EU) for a carbon-neutral society in 2050 and reviewing national energy and climate plans of several target countries (Germany, Spain, Belgium, Portugal, and Poland).
- The definition and identification of the relevant technology options to study the existing interrelationships among them and determining the subset of technology options responsible for severe impacts on the distribution system.
- The assessment of the expected future scenario for the EU, to understand the different deployment levels expected for each technology option. The most ambitious EU scenarios that respectively foster electrification, energy efficiency, use of hydrogen, and use of power-to-X technology are reviewed to understand the needs of the future distribution system.
- The discussion on the main challenges concerning the future distribution system and the provision of recommendations to address these challenges focusing on the consequences due to the deployment of the technology options.

The description of the EU long-term vision for climate and energy and the analysis of the long-term national, the analysis of the technology options and the analysis of the EU long-term scenarios allow to puzzle out the main features that will characterise the long-term backdrop of the future of the distribution system. The full document concerns the required changes in planning and operation practices, the adoption of mechanisms for flexibility procurement, the required innovations in regulation, and the required changes in business models of the main distribution system actors.

The activities described in this deliverable aims to provide insights and recommendations highlighting challenges and opportunities from the technical, regulatory, and market perspective to contribute to the evolution of the distribution system from now to 2050 and beyond.

The vision for a carbon-neutral EU in 2050

High-level policy goals drive the evolution that the electricity system is experiencing; hence, this document firstly describes the long-term vision for a carbon-neutral EU in 2050 corresponding to the energy and climate policy goals. The European strategy is based on seven main action blocks: energy efficiency, deployment of renewables, sustainable mobility, circular economy, interconnection of infrastructures, carbon capture storage technologies, bio-economy and carbon sinks. Not all these action blocks directly impact the distribution system; however, these action blocks are intertwined, and therefore indirect impacts on the distribution system are required to be investigated. The analysis of the ling term energy and climate plans of the target countries included in the EUniversal project (Germany, Spain, Belgium, Portugal, and Poland) allows to identify policies and technologies which adoption is expected in the future European electricity system. The most relevant technologies to achieve the national climate goals for each of the target countries are identified considering economic sectors such as transportation, buildings, and energy. Based on scientific literature, the univocal definition of each technology option is provided to ease the communication on the related concepts and harmonise the terminology used in the different national plans, since among the national plans often the same technology option is described with different terms. Furthermore, the mapping of the content of the long-term national plan considering the proposed concise list of technology options is addressed. Moreover, the comparison of the five national plans allowed to analyse similarities and differences regarding the technology options to be adopted in the future energy system of the different countries. Historical and geographical (and then climate) peculiarities influence the role that each technology option plays in the different national plans. Several technology options will be developed in all countries (e.g., battery electric vehicles, heat pumps, energy efficiency measures for buildings, renewable energy at the household level, energy storage systems). Contrariwise, other technology options are crucial only for some of the national energy plans of countries (e.g., large renewable power plants, CHP, biomass, heating and cooling networks). These differences highlight that one solution does not fit for all countries to achieve the policy and climate goals.

The vision for a carbon-neutral EU in 2050 and the relevant national energy and climate plans for the target countries are discussed in the full document in chapter 2: The long-term vision for a carbon-neutral EU in 2050.

Analysis of the relevant technology options considering the impact on the distribution system

The analysis of relevant technology options considering the impact on the distribution system is addressed starting from the list of technology options proposed as a common framework for mapping the initiatives in the national plans. The proposed high-level analysis considers the impacts to the distribution system at the system level, it assesses the technology options irrespective of local conditions such as the actual level of deployment of the technology options and the status of the grid. This analysis aims to identify the main aspects that have to be considered in quantitative estimations of the flexibility needs, which, in turn, requires detailed information regarding the context and the technical knowledge of the grid. Therefore, the high-level analysis concerns the impacts due to each single technology option without considering the future scenario and the actual grid characteristics; it is, therefore, scenario and grid agnostic. This analysis is complemented by the scenario analysis further addressed in the full document..

Firstly, the linkages among the technology options is qualitatively assessed. Each technology option represents a specific measure introduced to create impacts on the energy sector. However, the generated impacts may affect more than one subsector and influence the impacts and the deployment of other technology options. In the qualitative analysis, the technology options have been pairwise compared, considering a five-point scale that describes the nature and the intensity of the relationship (i.e. interdependency, mutual reinforcing, neutrality, weak competition, strong competition).

The linkage analysis points out the relationships among the technology options in terms of their mutual influence. Since each long-term scenario devises a different level of deployment for each technology option, the influence on the other technology options affects the overall scenario impact on the planning and operation activities of the distribution system.

The technology options identified and categorised represent the set of measures that will be implemented in the next future as declared in the long-term national plan. However, not all these technology options have an impact on the distribution system. Therefore, each of the technology options in the list retrieved from the analysed national long-term plans is assessed to determine the potential impact on the distribution system. The impact on the distribution system (operation and planning) is defined as the requirement of dedicated countermeasures to face the technology option deployment. The criteria adopted to identify the relevant technology options are the connection to the distribution grid, the asset typology (load, generator, or both), the capability to generate bidirectional electric power flows, and the ability to provide short-term flexibility. The corresponding impact on the distribution system is then classified considering two attributes that describe if the technology option affects the planning stage, the operation stage, or both, and if the impact is direct (i.e. it concerns connected resources) or indirect (i.e., the technology option affects the distribution system through the effects caused by synergic or competing technology options). This assessment led to a subset of technology options of interest for evaluating the impact on the distribution system considering the different scenario paths.

The analysis of the relevant technology options is discussed in the full document in chapter 3: Analysis of the technology options considering the impact on the distribution system.

Flexibility needs in long-term scenarios

Understanding the impact on the distribution system caused by developing the different technology options requires studying the expected future scenarios. The analysis of the future scenarios allows understanding the different deployment levels expected for each technology option. Therefore, the impact on the distribution network and the corresponding need for flexibility depends on the characteristics of the considered future scenario.

In the full document, the scenario paths defined by the European Commission for the *Clean Planet for All* package are described and analysed. The analysed scenarios have 2050 time-horizon and are designed to reach a carbon-neutral society. All the scenarios are studied; however, the main focus is on the scenarios ELEC, H2, P2X, and EE, which have been selected for the scope of the activities described in this document since defining the most stressful conditions for the distribution system. These scenarios pursue the most ambitious goal regarding the world temperature increase ("well below 2°C" ambition) and consider achieving this goal by adopting only energy generation and demand-side actions. Each scenario expects to reach the policy goals relying on a strategy based on a sectorial set of action. The ELEC scenario is based on the electrification of the energy demand, the EE scenario relies on the adoption of energy efficiency measures, the H2 and P2X scenarios promote respectively as primary options the use of hydrogen and power-to-x technologies. The ELEC, H2, P2X, and EE represents the extremes within which the actual future would lay. Uncertainties and specificities related to the local conditions make it likely to assume that none of these scenarios will actually occur. However, the actual future scenario can approximate one of those scenarios that define the vertexes of the uncertainty box. Each scenario is analysed to determine the technology options adopted and understand the corresponding deployment level. Then, considering each technology option independently, the impact on the distribution system in terms of flexibility needs is studied considering the four factors: electricity demand increase, an increase of generation from renewable sources, the increase of solar generation at the distribution level, the increase of technology options able to provide flexibility. The first three factors determine an increase of the flexibility needs of the distribution system, while the latter factor determines by itself a reduction of the residual need for flexibility in the distribution system.

The findings of the scenario analysis point out that the most relevant technology options to be considered for the related impact in the distribution system are the battery electric vehicles, heat pumps, building refurbishment, renewable generation at the household level, combined heat and power (CHP), and building automation. Moreover, the scenario analysis highlights that to quantitatively estimate the impacts of technology options on the distribution system; it is necessary to complement the information available from the high-level scenarios, particularly by estimating the quota of local generation expected to be connected in the distribution system, the deployment of CHP, and the adoption of building automation technologies. Reliable information on these technology options can be available only at the local level, in line with the requirements for moving from a qualitative to quantitative estimation of the impacts on the distribution system. Therefore, it is highlighted that assessing the flexibility needs for the future distribution system requires both a top-down and a bottom-up approach. The top-down qualitative approach allows understanding the objective to be achieved, the boundaries of the strategies, and the high-level challenges. The top-down approach guides the bottom-up approach the requires information on the local conditions such as the actual level of deployment of the technology options and knowledge of the grid (e.g., the status of the network, zonal load and generation type and capacity) to determine quantitatively the flexibility need of a specific distribution network and the already available flexible resources. This document represents a top-down analysis to identify the distribution system needs in the long term. The aim is to identify the main aspects that have to be considered in the bottom-up quantitative approach for estimating the flexibility needs of a specific network; which, requires detailed information regarding the context and the knowledge of the grid.

The assessment of the flexibility needs in long-term scenarios is discussed in the full document in chapter 4: Flexibility needs in long-term scenarios.

Challenges and solutions for the long-term future of the electric distribution system

The analysis of the long-term vision for a carbon-neutral EU in 2050, the national energy and climate plans, the study of the technology options, and the future scenarios expected in the EU allow formalising a set of general recommendations to guide the evolution of the EU future distribution system. These recommendations for the long term vision of the distribution system concern the technology option deployment to take full advantage of the changes expected for the distribution system, the modernisation of distribution system planning and operation, the flexibility procurement mechanisms to be adopted, the evolution of regulation and business models.

The findings and recommendations for the future electric distribution system are discussed in the full document in chapter 5: Challenges and recommendations concerning the future distribution system.

Technology options deployment in the future electric distribution system

The high-level analysis of the impact on the distribution system presented in the full document provides an overview of the development of the different technology options considering different possible strategies. This analysis sets the basis for a more detailed analysis that can be addressed at the local level. In fact, quantitative appraisals of the future need for flexibility has to be local since it is fundamental to include the characteristics of the distribution system under analysis (e.g., regulation at country level, the status of the network, the zonal load and generation type and capacity). The analysis described in the full document identifies the technology options to consider carefully, how these technology options are intertwined, and how the deployment of the different scenarios for the energy system influence the technology option deployment and the related impact on the future distribution system.

In general, scenarios based on electrification may determine the most relevant impact on the future distribution system. However, smart energy system integration across sectors has to be pursued as a primary goal in each decarbonised scenario. The decarbonisation of our society requires better integration of the different sectors and the related infrastructures. Sector integration allows maximising the exploitation of the available resources contributing to the decarbonisation of the energy system. Additional research, innovation and demonstration are required to understand the crisscrossed impacts among the different sectors and infrastructures. Moreover, digitalisation represents an overarching trend in the EU; pursuing digitalisation allows monitoring and controlling the energy processes by enabling the management of the decentralised energy system. Therefore, to face the challenges of the future decarbonised scenarios, digitalisation of the distribution system is required to enhance the observability and controllability of the network infrastructure.

Operation and planning for the future distribution system

As also pointed out by the study of the future EU scenarios expected, operating and planning the future distribution system is subject to high uncertainties, mostly due to the various possible technology options deployed and the various operational schemas that could be adopted in the long term. The high-level analysis shows the principal requirements for flexibility, depending on the deployment and design of technology options in various long-term scenarios. A quantitative analysis of the flexibility needs that sufficiently considers the local conditions (e.g., the status of the network, zonal load and generation type and capacity) is essential for distribution network planning. Likewise, regulators need quantitative analyses to shape efficient regulations, enabling the cost-effective development of the sustainable energy system.

Several tools to support this quantitative assessment exist, other tools or models are emerging. EUniversal D1.2 presented a characterisation of distribution network control and management tools and technologies to enable the participation of Distributed Energy Resources (DER) in flexibility markets. This characterisation is used as a reference frame while projecting potential DSOs needs for operation and planning tools up to 2050.

Long term planning with a time horizon up to 2050 needs to consider the input data based on the respective scenario paths as well as the related feasible operational models. This will allow applying counter-measures and reducing potential overinvestment resulting from high switching costs based on technology lock-in on the time-scale of the planning horizon 2050. Long-term planning scenarios need to consider the degree of decentralisation of Distributed Energy Resources (DER) and the corresponding CAPEX and OPEX for ICT needed to coordinate a highly distributed system with very high security of supply requirements. Realistic large-scale distribution system models, so-called Reference Network Models (RNM), should be used to validate complex active network operation and planning. The knowledge of load and generation behaviour, the load, generation, and flexibility forecasting become essential for distribution system operation and planning. Therefore, load profiling, continuous forecast quality and availability assessment are needed for cost-effective and resilient operation and planning in the future distribution system.

Mechanisms for procuring flexibility from third parties in the future electric distribution system

As highlighted by the scenario and technology option analysis, all scenarios for the future distribution system concern developing technology options capable of providing system services to the DSO. Any mechanism for acquiring system services shall aim for technology neutrality, as discussed in EUniversal Deliverable 5.1, "Identification of relevant market mechanisms for the procurement of flexibility needs and grid services". Due to the great variety of resources that can support the power system by providing system services, DSOs can use a wide range of mechanisms to acquire flexibility from resources owned by other players of the distribution systems (e.g., distributed generators, prosumers, customers, aggregators). The key mechanisms of interest of EUniversal identified are flexible access and connection agreements, dynamic network tariffs, and local flexibility markets. Flexibility markets should be preferred unless the conditions make them impossible. Moreover, the local characteristics have to be carefully assessed to ensure enough liquidity and prevent market distortions. Dynamic network tariffs and connection agreements could involve small business and residential customers in providing flexibility since the low complexity for the final electricity users.

Innovation in regulation for the future electric distribution system

The review of the EU long term vision and scenarios and the analysis of the possible technology options point out the tremendous transformation required to the distribution system. Modernisation of regulation has to accompany the energy transition and distribution system evolution, taking advantage of the available opportunities without jeopardising the supply quality and security and increasing the overall system costs. The novelty of mechanisms for procuring system services from resources connected to the distribution system makes pioneering designing mechanisms such as local markets; thus, it requires to resort regulatory experimentation to explore all possibilities, assess local conditions, and determine strengths and weaknesses of the possible mechanisms. Regulatory experimentation helps national regulatory authorities and DSOs to obtain evidence to support elaborating the regulation needed in the future distribution system.

Regulatory sandboxes are legislation instruments to experiment with innovative business models or technologies, which legal or regulatory barriers would hinder under normal conditions. Innovation and business model development can be achieved by granting stable conditions for a limited time (and often limited geography) by opening, repealing, or disabling rules and regulations or keeping existing regulations and compensating the participants. Regulatory experimentation and the adoption of regulatory sandboxes are seen as useful means to address the relevant issue of distribution networks in a decarbonised scenario. Main challenges to be addressed regard market integration, project appraisal, distribution network planning, flexibility remuneration, and TSO-DSO coordination.

Novel business models for the actors of the future electric distribution system

The analysis of the EU long-term scenarios and the corresponding level deployment of the technology options make evident that the evolution of the distribution system implies the emergence of new actors and business models; moreover, changes are necessary for the business models of the existing electricity actors depending on the new roles covered and assigned responsibilities.

The role played by the DSO is peculiar considering the responsibilities for ensuring security and quality of the electricity supply and the requirement to guarantee universal access to the grid to the other actors of the electricity sector. The DSO business model is strongly influenced by the assigned responsibilities and the boundaries fixed by regulation for its role. In fact, the DSO business models change if grid ownership and grid operation are assigned to different entities and if the role of the local market operator, local energy manager, or data manager are also covered by the DSO.

Regarding Flexibility Service Providers (FSPs), the actual business model will depend on the flexibility procurement mechanism in force (e.g. obligation, network tariffs, connection agreements, or market-based procedures). Moreover, in flexibility markets involving resources connected to the distribution system, the aggregator of flexible resources may play a central role. The aggregator is an emerging actor in energy systems that offers services to aggregate energy production and consumption from different sources (generators, loads, storage) and acts toward the grid as one entity. Also, for the aggregator, the corresponding behaviour and the business model differ according to the procurement mechanism adopted, the service provided, the boundaries imposed by regulation, and the local conditions (e.g., distribution grid scarcities, flexible resources availability).

Conclusions and contributions of EUniversal Task 1.3

This deliverable provides a long-term vision for technologies, particularly utility-scale and distributed renewable generation, storage, electric vehicles, and smart grid developments, based on the analysis of six EU target countries (i.e., Germany, Spain, Belgium, Portugal, and Poland). The challenges and opportunities for system and network operators are identified under current regulatory frameworks and market rules, so that future flexibility needs are characterized. The contributions of the present deliverable are:

- the analysis of the long-term European strategy for a carbon-neutral society (section 2.1),
- the definition of the main technology options and the formalisation of a unified list (section 2.3),
- the analysis of long-term plans of the EUniversal project target countries (Germany, Spain, Belgium, Portugal, Poland) and the mapping with the technology option defined (Table 2-9),
- the identification of the technology options which can impact the distribution system (Table 3-4),
- the analysis of the high-level EU scenarios for 2050 to identify the deployment level expected for the technology options (section 4.3.1),
- the high-level appraisal of the impact that each scenario would have on the distribution system (section 4.4),

- the discussion on findings and recommendations regarding technology options, planning and operation of future distribution networks, regulation for the future distribution system, business models for the actors of the future distribution system (section 5).

The achievements mentioned above serve as an input to WP4, WP5 and WP10, where best practices and detailed recommendations for operation and planning activities, new business models, market arrangements, and regulatory mechanisms are provided.

The closing remarks are discussed in the full document in chapter 6, titled "Conclusions".

1 Introduction

The EUniversal project, funded by the European Union, aims to develop a universal approach on the use of flexibility by Distribution System Operators (DSO) and their interaction with the new flexibility markets, enabled through the development of the concept of the Universal Market Enabling Interface (UMEI) – a unique approach to foster interoperability across Europe.

The UMEI represents an innovative, agnostic, adaptable, modular and evolutionary approach that will be the basis for the development of new innovative services, market solutions and, above all, implementing the real mechanisms for active consumers', prosumers', and energy community's participation in the energy transition.

The EUniversal project has the primary objective to overcome the existing limitations in the use of flexibility by DSOs. A Universal Market Enabling Interface will be implemented to foster the provision of flexibility and link the active system management of distribution system operators with electricity markets. In this context, the present deliverable analyses the recent and ongoing European policy and strategical initiatives that will shape the future electricity grid and markets.

The present deliverable is part of the Work Package 1 (WP1) contribution to the EUniversal project. Figure 1-1 depicts the flowchart of the correlations among EUniversal project tasks. EUniversal WP1 is entitled "Future vision for flexible grids and well-functioning seamless electricity markets", and aims to: review recent and on-going policy and regulatory initiatives that may shape the grids and market of the future (Task 1.1); assess and draw lessons learnt from recent and on-going research and demonstration initiatives relevant to the project objectives (Task 1.2); and define a future vision for challenges and opportunities for European electricity grids and markets (Task 1.3). The goal of WP1 within the EUniversal project is to set a common framework in terms of policy, regulation, markets, product/services, technologies and future vision.

The present deliverable concerns the findings of EUniversal Task 1.3 activities, "Definition of challenges and opportunities for grids and markets", led by COMILLAS with the contribution of EASE, E.DSO, ENERGA, E.ON, E-REDES, IEN, INESC, and VLERICK. This task collects the inputs from the previous two tasks to define a long-term vision beyond 2030 characterizing the challenges and opportunities of distribution grids and electricity markets (technologies, stakeholders, business models, regulation, market design) in a decentralized, decarbonized and digitalized power system. This task develops for each of the EU target countries a long-term vision for technologies, particularly utility-scale and distributed renewable generation, storage, electric vehicles, and smart grids. The challenges and opportunities for system and network operators are identified under current regulatory frameworks and market rules, so that future flexibility needs are characterized. The identification mentioned above serves as an input to WP5 and WP10, where best practices and recommendations for new business models, market arrangements and regulatory mechanisms are provided.

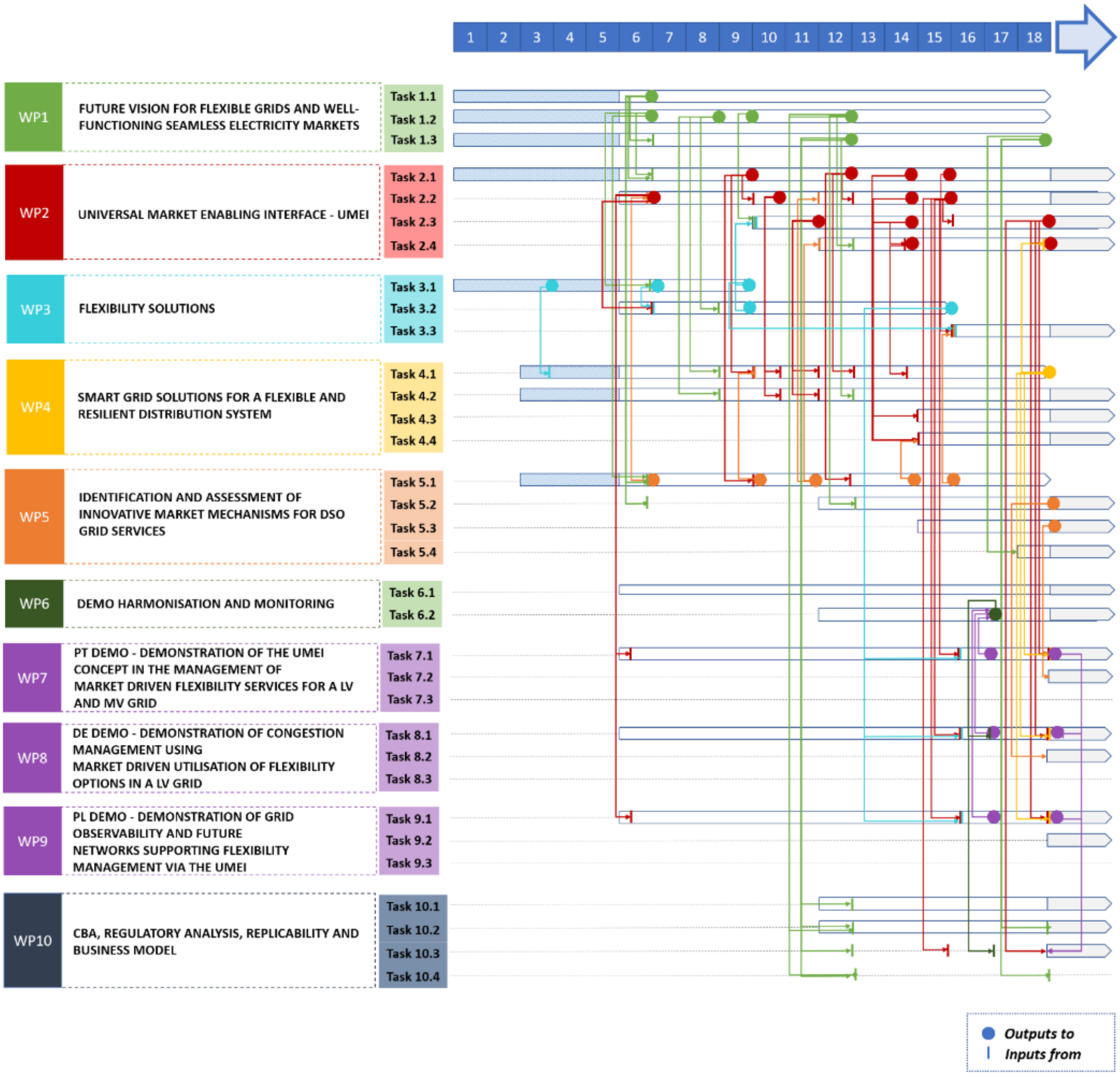


Figure 1-1. Correlations among EUniversal project tasks

The structure and the main aspects addressed by the present deliverable are described in Figure 1-2. Climate change concerns represent a big challenge since severe consequences are expected in terms of increased frequency and intensity of extreme weather events that would undermine productivity, infrastructures, health, biodiversity, ability to produce food, and political stability [1], [2]. Worldwide efforts are ongoing to address the climate change challenges and avoid the expected dire consequences; several national and international plans have been devised and proposed to adopt effective actions to reduce the carbon footprint of our society [3]. In this context, the decarbonisation of the electricity supply is a pivotal action, which mainly relies on increasing the electrical energy generated by renewable resources and pursuing energy efficiency [2]. In decarbonization scenarios, the need to maximise the exploitation of the intermittent energy sources and the available resources and infrastructure makes it indispensable to abandon the traditional load following paradigm to adopt mechanisms that foster the active participation of all connected resources to the electric power system operation [4]. The resources connected to the power system have to be capable of adapting their electricity exchange to the needs of the power system operation. The active participation of the connected resources is a means for addressing the power system transformation at a reasonable cost, without harming the security and quality of the electricity supply, unlocking the potential flexibility of the already available resources, and fostering the availability of new resources [5]–[7].

In the decarbonised scenarios, the distribution system will face unprecedented changes due to the advent of distributed energy sources fed by renewables and new loads due to the trending electrification of the energy demand [8]. On the one hand, providing distribution network to distributed generation and new loads requires huge investments; on the other hand, if these resources are effectively integrated with the distribution system planning and operation, they can contribute to relieving their own impact and reduce the investments required for upgrading distribution system [5], [6], [9]–[11]. These investments are part of the investments required to keep updated the distribution system to guarantee the quality and reliability standards of the electricity supply.

The assessment of the flexibility needs for the future distribution system requires both a top-down and a bottom-up approach. The top-down qualitative approach allows understanding the objective to be achieved, the limits of the strategies, and the high-level challenges. The top-down approach guides the bottom-up approach that requires local information such as the actual level of deployment of the technology options and knowledge of the grid (e.g., the status of the network, zonal load and generation type and capacity) to determine quantitatively the flexibility need of a specific distribution network and the already available flexible resources. This document represents a top-down analysis to identify the long term needs of the distribution system. The aim is to identify the main aspects that have to be considered in the bottom-up quantitative approach for estimating the flexibility needs of a specific network; which, requires detailed information regarding the context and the detailed knowledge of the grid from the technical perspective.

The present deliverable aims at contributing to the evolution of the distribution system by understanding the flexibility needs of the future distribution system. The main activities leading to this deliverable are resumed in Figure 1-2. The present deliverable is organised according to the flowchart depicted in Figure 1-2.

The second chapter of this document concerns the description of the drivers of the power system transformation and the requirement for the flexibility needs of the future distribution system. Therefore, the EU policy and climate goals are described. Moreover, the National Energy and Climate Plans of target countries included in the EUniversal project activity (Belgium, Germany, Poland, Portugal and Spain) are analysed. The analysis of the national plans relies on the definitions of the technology options based on scientific literature; the mapping of the content of the long-term national plan considering the proposed concise list of technology options is addressed to ease the communication on the related concepts and harmonise the terminology used in the different national plans. The long-term national energy and climate plans are examined to identify policies and technologies expected in the future European electricity system.

The third chapter of this document includes the system-level analysis of the technology options in the relevant national plans adopting a scenario- and grid-agnostic approach. The linkages among the technology options are qualitatively assessed. Each technology option represents a specific measure introduced to create impacts on the energy sector. However, the generated impacts may affect more than one subsector and influence the impacts and the deployment of other technology options. Subsequently, the technology options are assessed considering their capability to influence the electric distribution system planning and operation. The outcome of this assessment is a subset of technology options that will impact the future distribution system.

The fourth chapter of this document identifies the impact of the expected future scenarios on the distribution system by studying the technology options that will be adopted in each scenario. The scenarios relevant for the European Union are analysed to understand the set of technology options adopted in the different scenarios and identify the different levels of deployment expected for each technology option. The magnitude of the generated impacts depends on the level of deployment expected for each technology option in the different scenario paths defined in [1]. Therefore, the impact on the distribution network and the corresponding need for flexibility that depend on the characteristics of the future scenario are considered and discussed.

The fifth chapter of this document collects the findings of the activities described in the previous chapter to formulate best practices and recommendations to address the identified challenges to be faced by the future distribution system and maximise the benefits in the long term due to the deployment of the decarbonisation policies. Challenges and opportunities for grids and markets are identified and discussed. Moreover, the required innovations for the operation and planning of future distribution networks are described.

Finally, chapter six resumes the findings of the EUniversal Task 1.3 activities by providing closing remarks and final recommendations.

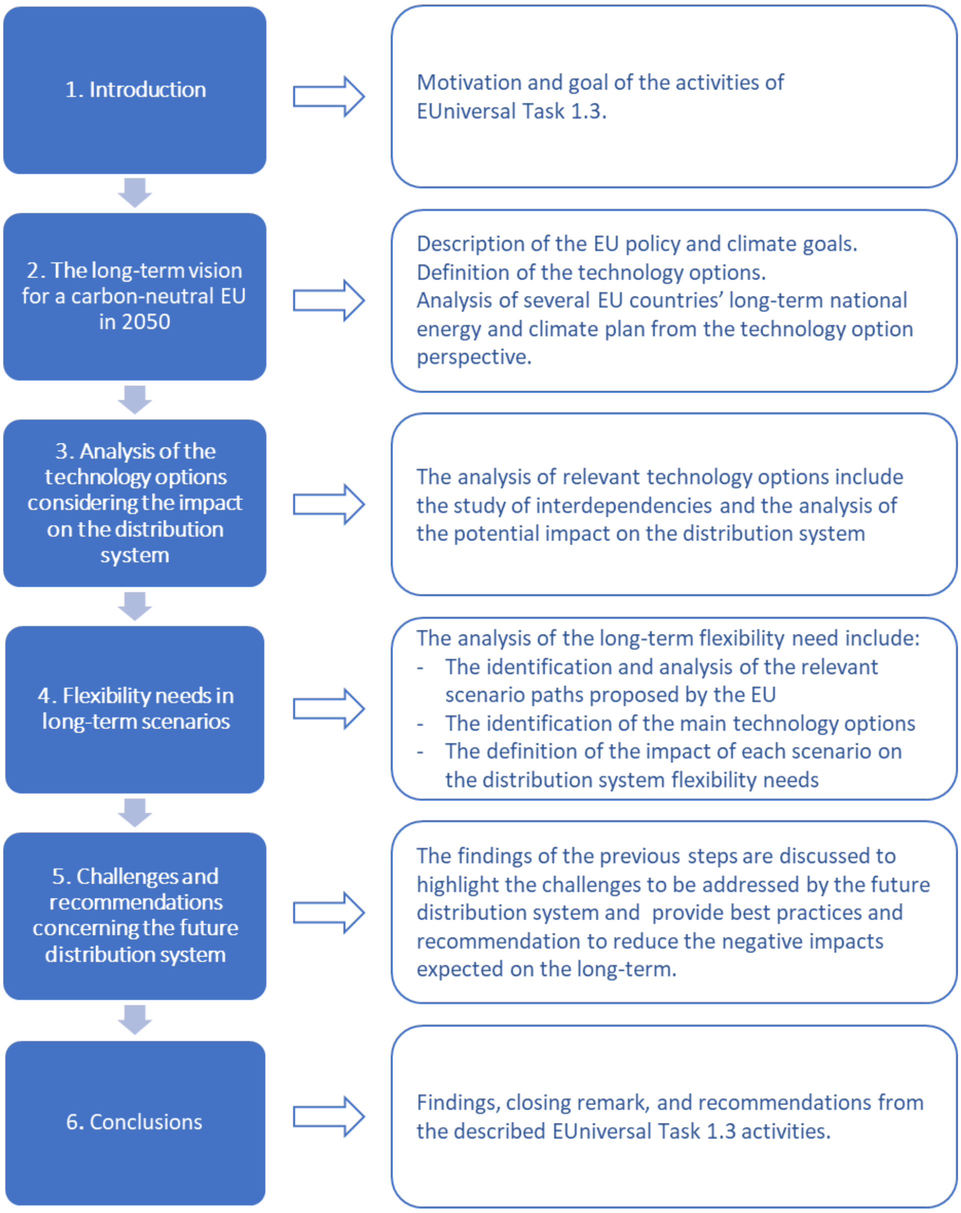


Figure 1-2. Structure of the EUniversal Deliverable 1.3

2 The long-term vision for a carbon-neutral EU in 2050

Climate change concerns represent a big trend since severe consequences are expected in terms of increased frequency and intensity of extreme weather events, undermining productivity, infrastructures, health, biodiversity, ability to produce food, and political stability [1], [2]. In line with the commitment of the 2015 United Nations Climate Change Conference (COP21) agreement to face risks and threats expected due to climate change, the European Union (EU) proposed to the secretariat of the United Nations Framework Convention on Climate Change (UNFCCC) a long-term strategy which objective is to achieve net-zero greenhouse gas emissions by 2050, by a cost-efficient and socially-fair transition [1], [12]. Since the greenhouse emissions of the energy system represent about 80% of the overall EU GHG emissions, the energy policy plays a crucial role in the European Union strategy for undertaking decisive climate actions [1], [2].

The terms of the UNFCCC COP21 agreements require that each Member State draw up the national mid-century long-term plan for reducing greenhouse gas (GHG) emissions in line with the common EU strategy [1], [2], [12]. These long-term GHG emission reduction plans have to be consistent with the national energy and climate plans for 2021-2030 established in [13]. In particular, the EU regulation defines the process for preparing long-term climate and energy plans and establishes the obligation for the Member States to create a new plan every ten years.

The EU and the Member States have the ambition to lead the transition to climate neutrality by taking advantage of the opportunities related to the potential economic growth, new business models and markets, new jobs, and the technological development that the adoption of the measures defined in the long-term plans would bring [12].

2.1 EU long-term vision and commitment to the UNFCCC

The EU strategy aims to achieve a climate-neutral economy with net-zero GHG emissions by 2050 through actions that would radically change key sectors, such as energy, transport, industry, and agriculture [1], [2]. The actions for accomplishing the EU objective are based on adopting existing and emerging technology solutions, citizens empowerment, and coordination of the industrial, finance, and research strategies [14]. The European Union long term strategy to 2050 represents a high-level vision for the future European society and economy; the general objective of achieving net-zero greenhouse gas emissions by 2050 is fixed [1]. Moreover, the main actions that compose the EU strategy are identified in the accompanying documents to guide the Member State strategies [2], [14]. Concrete 2050 targets are not defined for all actions; however, the EU commission periodically delivers general and sector-specific medium- and short-term plans and targets [15], [16]. Furthermore, Member States periodically define the national strategy and define some of the corresponding targets in the National Energy and Climate Plans, which comply with the overall objective of the EU strategy [13]. In line with the scope of this deliverable, it is of interest to understand the main drivers that would lead the development of the different technology options in the Member States. Due to the uncertainty inherent in the definition of such a broad long-term vision, this section focuses on the actions that characterise the EU strategy rather than on the numerical expectations and ambitions reported in [2], [14]. A detailed analysis of the scenario paths that would lead the EU economy towards net-zero GHG emissions is provided in section 4.

The EU 2050 long-term strategy is formed by seven blocks [14]:

1. Energy efficiency: maximise the benefits of energy efficiency, including zero-emission buildings.
2. Deployment of renewables: maximise the deployment of renewable energy sources and increase the use of electrical energy for fully decarbonising the energy supply.
3. Mobility: achieve clean, safe, and connected mobility.
4. Circular economy: introduce the circular economy paradigm by achieving a competitive industry.
5. Network infrastructures: develop highly interconnected smart network infrastructures.

6. Bio-economy and carbon sinks: the adoption of bio-economy concerns the use of renewable biological resources from land and sea to produce food, materials and energy [17], and the creation of carbon sinks (e.g., forests and other ecosystems) for absorbing the emitted carbon.
7. Carbon Capture and Storage (CCS): the adoption of CCS technology to deal with the remaining GHG emissions.

Implementing the EU strategy, the Member States are committed to climate goals by choosing the most appropriate energy mix and technologies for ensuring energy security and competitiveness [12].

The Energy efficiency action block aims to achieve a 50% demand reduction from 2005 to 2050 [2]. Besides the already introduced eco-design and energy labelling measures, new standards and technologies, such as digitalisation and building automation, will be exploited to increase energy efficiency [14]. Energy efficiency measures will be adopted in the context of the decarbonisation of the industrial sector and the reduction of buildings' overall energy demand. Regarding the energy efficiency of buildings, energy performance standards are introduced. The existing constructions will be renovated considering a climate-friendly approach that includes the use of sustainable renewable sources for heating, efficient appliances (e.g. heat pumps), smart management systems for buildings and appliances, and better insulation [14]. Achieving the energy efficiency objective requires financial instruments, a qualified workforce, and consumer engagement [14].

The aim of the renewable strategy block consists of making renewables the principal source of primary energy. This objective allows to improve the security of supply (by reducing the share of imported energy from 55% to 20% in 2050), domestic jobs, and reduce GHG emissions [14]. The increase in the share of primary energy generated by renewable will increase electricity production; then, electricity will cover 50% of the EU final energy demand in 2050 [14]. The renewable energy sources will cover 80% of the overall electrical energy generated in the EU [14]. Therefore, increasing the share of renewable energy in the energy system requires exploiting electrical energy; electrification of the final energy demand is required. Electrical energy production has to increase by up to 2.5 times to sustain the expected increase in electricity demand [14]. The guidelines for accomplishing this deployment of renewables include decentralisation of the electrical system and empowerment of local communities, customer engagement with active participation in energy markets, electrification of the demand of several sectors (transport, climatization of buildings, industrial consumption) and introduction of e-fuels (hydrogen and power-to-X), making the electric grid smarter and more flexible, improving the means of large-scale energy storage, improving the participation of demand response through digitalisation, and increasing the regional interconnectivity [2], [14].

The mobility block has the objective of achieving clean, safe, and connected mobility. The relevance of the transport sector relies on the fact that it is still mainly based on fossil fuels [2]. Excluding international aviation and maritime, GHG emissions from transport in 2017 were 20% higher than in 1990, and the overall GHG emission from transport are expected to rise [2]. The transition towards a more sustainable mobility system based on low or zero-emission vehicles (e.g. electric vehicles) would also lead to having cleaner air, reduce the noise related to traffic, and reduce the number of accidents [14]. The EU strategy for transportation envisages biofuels, climate-neutral e-fuels for aviation, while hydrogen and biogas would be used for shipping and heavy-duty vehicles [14]. Besides the use of climate-neutral fuels, mobility will be modernised by adopting smart traffic management systems that would bring an efficient organisation enabled by digitalisation, data sharing, and interoperability [14]. In particular, urban mobility will be introduced in smart city planning, and it will focus on safe paths for walking and cycling, clean public transport, and mobility services such as car- and bike-sharing [14]. The success of the mobility strategy depends on the internalisation of the external costs of transport and customer awareness [14]. For example, an effective high-speed train system could represent a more sustainable alternative for long internal European flights [14].

The circular economy objective is focused on moving the economic system towards a more sustainable model while preserving the competitiveness of the EU industrial sector. This paradigm shift will introduce recycling practices, especially for steel, glass, and plastic, which production will become more efficient and less emissive [14]. Raw material recovery and recycling represent the keywords for the circular economy objective. The industrial installations need to be modernised or replaced by introducing digitalisation and automation. The industrial process has to be electrified and use hydrogen, biomass, and renewable syngas to reduce GHG emissions [14]. As a last resort, CCS technology will be introduced to capture emissions that could not be eliminated. Moreover, the introduction of more sustainable materials which the related production processes are less emissive and less energy-intensive will be favoured.

The infrastructure and interconnection objective aims to build smart and interconnected network infrastructures to increase cross-border and regional cooperation and encourage sectoral integration [14]. This objective will be reached by improving and extending cross-border links in Europe, improving electric transmission and distribution grids as well as the related communication networks, building hydrogen networks, and, where necessary, intensifying sector-coupling, for example, enhancing the synergies between the energy and transport sectors [2].

The bio-economy and natural carbon sinks objective is aimed at facing the issues related to the increasing demand for goods by the population and the parallel decreasing productivity due to climate change consequences. Therefore, it is of utmost importance for agriculture and forestry to adopt sustainable production of food, feed and fibre [14]. Biomass plays a central role since it can be an alternative to emission-intensive materials and can also be used for heating. It can also substitute natural gas by transforming it into biofuels and biogas [14]. It has to be combined with CCS systems to ensure biomass's zero/negative emission footprint [14]. According to the bio-economy and natural carbon sinks objective, the agricultural sector has to reduce nitrous oxide and methane, increase productivity, and reduce the generated air and water pollution [14]. The measures range from digitalisation, precision farming technologies, anaerobic manure treatment, and the adoption of sustainable agroforestry techniques, soil-adaptive agricultural activities, and the restoration of wetlands and peatlands [14]. Moreover, creating carbon sinks through afforestation and restoration of degraded forest lands and similar ecosystems would generate negative emissions while preserving biodiversity.

The Carbon Capture Storage block of the EU long-term strategy represents the resource for breaking down the residual emissions and for producing hydrogen [14]. Investments are required for improving the effectiveness of CCS [14].

An adequate framework of policies and transformation synergies among the different sectors of the society has to be enabled to achieve the goal of net-zero EU GHG emissions by 2050 through the strategy formed by the seven building blocks described in this section. The commercial rules have to shape a circular economy system and favour sustainable technologies in energy, buildings, and mobility [14]. The trading rules have to guarantee freedom, fairness, and competitiveness while ensuring compliance with the climate goals [14]. Taxation has to internalise the cost of externalities and redistribute the energy transition's burden [14]. A single digital market is seen as the key instrument for reaching the required system integration and the realisation of new sustainable business models [14]. Society plays a crucial role in the transition to a climate-neutral EU, citizens have to be empowered and involved actively in the new business models as well as have to adopt more sustainable lifestyles which would contribute locally to the transformation [14]. Finally, research and innovation have to be incentivised since they make available the technologies which enable and make faster the transition to a zero-carbon society [14].

2.2 National Energy and Climate Plans: beyond 2030 up to 2050

For achieving the objective of being climate neutral by 2050 through the strategy described in section 2.1, the EU requires the Member States to present periodically national plans in which actions and measures to be adopted are specified and concretely described.

To coordinate the efforts of the EU against the climate change consequences, the EU Regulation 2018/1999 [13] introduces the requirement for the Member States to devise National Energy and

Climate Plans (NECPs), which have to be reported every two years and cover a ten years horizon. These plans have to define the national measures to be adopted in the context of increasing energy efficiency, exploitation of renewable energy sources, reduction of greenhouse gas emission, enhancement of interconnections, and commitments in research and innovation. Citizens and stakeholders have to be involved in the process of development and implementation of the plans. The adoption of the measures in the NECPs is checked every two years by the EC based on the progress report that each Member State has to present. The actual NECPs cover the period 2021-2030 [18].

In addition to the NECP commitment, in compliance with the UNFCCC COP21 agreement, the Member States are also required to prepare and submit the long-term national strategies for 2050. The objective of the long-term plans is the development of strategies for reducing GHG emissions, which have to be consistent with the measures defined in the NECP. The mid-century long-term plans have to focus on reducing the total GHG emissions and building carbon sinks [19]. Emission reduction measures in all main sectors have to be covered in the plan, particularly electricity, industry, transport, heating and cooling, buildings (residential and services[1]), agriculture, waste, and land use [19]. Strategies for achieving a low GHG emission economy by investments, research, and innovation have to be proposed [19]. Moreover, the socio-economic impact of the decarbonisation measures has to be analysed in the plan as well as the coordination with the other national long-term objectives has to be highlighted [19].

The long-term national strategies already received by the EC are publicly available [19]. Since these plans describe, for each sector, the measures to be adopted in the next 30 years, their analysis provides, as output, the list of technology options that will be crucial for the future European electric distribution system. In fact, irrespective of the particular scenario path that specifies the level of deployment expected for each technology, the list of options represent the basis of the long-term projections. To identify the list of technology options that will be exploited for achieving climate neutrality by 2050, the mid-century long-term plans of Germany, Belgium, Spain, Poland, and Portugal are analysed. The outcome of the analysis of those plans is described in section 2.5.2, which serves as input for identifying the subset of the technology options that would impact the planning and operation practices of the electric distribution system of the next decades.

2.3 Definition of the technology options

The analysis of the national plans allows listing the technology options of interest for achieving the climate objectives. As the analysis of the national plans in section 2.5 will reveal, the national plans rely on almost the same set of technology options, while only some are not present in more than one plan. Moreover, even if the same technology option may be present in different plans, it may appear with a slightly different name. In this section, a univocal definition of the technology options based on scientific literature is provided to harmonise similar technology options and obtain a concise list from the analysis of the long-term national plans addressed in section 2.5.

The **Battery Electric Vehicles (BEV)** technology option represents a vehicle driven by electricity using a battery that can be externally charged [21]. In this category, full-electric vehicles are considered.

The **Plug-in Hybrid Electric Vehicles (PHEVs)** technology option concern the vehicles equipped with batteries, electric motor, and internal combustion engine fuelled with gasoline, diesel, or other fuels [22], [23]. PHEVs can recharge the batteries from pluggable external electric sources (e.g., the

[1] "Services" refer to the service sector, also known as the tertiary sector [20]. It produces no goods, but provides a service that satisfies a need encompassing maintenance and repairs, training, or consulting. It includes diverse organisations and enterprises.

electrical grid) or through regenerative braking and the internal combustion engine. PHEVs significantly reduce fuel consumption in regular driving conditions; PHEVs have been considered a transitional technology towards BEV [22].

The **FC-EV (Fuel Cell Electric Vehicles)** technology option encompasses all-electric vehicles equipped with fuel cells. The fuel cell electric vehicles are characterised by an electric motor powered by fuel cells that convert the chemical energy of the primary fuel into electrical energy [24].

The **Combustion engine + power-2-X** technology option describes hybrid electric vehicles equipped with a conventional combustion engine vehicle with synthetically produced fuels (liquid or gas) based on zero-carbon electricity [25]. **Power-to-X** for the transportation sector encompasses all technologies that convert electric energy in synthetic fuels that can be exploited for mobility. Power-to-X technologies are typically dedicated to non-plug-in hybrid electric vehicles to be utilised for freight and passenger transportation.

The **Biomass for long-haul transport** technology option includes the use of biomass for producing energy to be used in the transportation sector; this is especially highlighted for long-haul transport in the aviation and marine transport modes [2], [26].

The **Multimodal transport** technology option refers to all the measures that incentivise the integration of different collective passenger modes (e.g., trains, planes, ships, bus, car-sharing, metro) and the integration of different freight transport modes (e.g., trucks, trains, ships, trains). In this report, the national plans refer to a multi-modal transport oriented to the maximisation of collective transport modes to reduce greenhouse gas emissions and increase overall energy efficiency [27]–[29].

The **Traffic interconnection and flow automation** technology option concerns all measures that optimise transportation modes [30], [31]. New mobility services are expected in which the traffic flows are automatized and optimised, considering the joint use of different transport modes and the energy and emission savings from flow automation. This technology option may be considered as a smart multimodal transport integration.

The **Shared mobility** technology option encompasses all the models for the shared use of cars and bikes [32]–[36]. This is especially relevant in so-called car-free cities.

The **Building refurbishment** technology option refers to all the processes and solutions for improving the energy efficiency and climate impact of a building [37], [38]. It may include activities such as upgrading, modernisation, conversion, insulation. It is worth noting that refurbishment has a climate impact as the materials and refurbishment work have a carbon footprint.

The **Building standards (zero or plus energy house)** technology option refers to the definition of building standards that lead to a building characterised by a zero (or positive) net energy consumption on an annual basis [39], [40]. Building standards, in contrast to building refurbishment, is only relevant for new constructions.

The **Passive solutions** technology option refers to all those design strategies that improve the comfort conditions by increasing the energy efficiency in buildings [41]. Passive solutions can be exploited for constructing new buildings or refurbishing existing ones.

The **Condensing boiler** technology option concerns all water heaters which use gas or oil as fuel [42]. Unlike conventional boilers, these devices exploit the condensation of water vapour in the exhaust gasses by recovering the latent heat of vaporisation, allowing them to achieve higher efficiency.

The **Solar water heating** technology option encompasses all systems formed by storage tanks and solar collectors, producing hot water using solar radiation [43], [44].

The **Heat pumps** technology option refers to all devices that transfer heat energy in the opposite direction of spontaneous heat transfer [45]., The heat pumps require the use of external power to accomplish this reverse heat transfer. The external power can be provided in different forms; however, the electricity fed heat pumps represent the dominant technology.

The **CHP (non-fossil)** technology option refers to all the combined heat and power (CHP) generators that are fed by non-fossil fuels, especially stationary fuel-cells but also conventional combustion engine-based CHPs fuelled by several fuels, such as biogas[2]/biofuel[3]/synfuel[4]/syngas[5] [51], [52].

The **CHP (High Efficiency)** technology option refers to all the combined heat and power (CHP) generators fed by fossil fuels that meet the requirement and hold the qualification of high-efficiency cogeneration, as established by the European and the National legislation [53]–[55].

The option **Electrification of the energy demand** represents all those policies (e.g. incentive schemes) that promote technologies that allow cooling and heating demand of buildings to be fed by electric energy [2], [56]. The National Energy and Climate Plans analysis described in section 2.5.2 highlights that this policy action mostly coincides with the adoption of heat pumps.

The option **Renewable energy at the household level** represents all those policies (e.g. incentive schemes) that aim to promote the technologies related to the development of renewable energy sources used at the household level (e.g., PV modules, small and micro wind turbines, small and micro CHP, solar water heaters) [57]–[61].

The **Building automation (or home automation)** technology option includes the automated coordination of the devices and systems that are part of a household, or in general, of a building [62], [63]. Building automation systems require monitoring relevant parameters for developing suitable control actions to be executed by the connected devices, helpful in achieving strategic goals such as increasing comfort or energy efficiency.

The **Heating and cooling networks** technology option represents all the assets employing a thermal fluid transportation system useful for distributing among consumers the heat and cold produced by a central generation, which could be large or small depending on the characteristics of the districts [64]–[66]. Often, additional distributed units are connected to the heating and cooling network, the operation of these distributed units is optimised considering the context of the whole network.

The **Decentralised, flexible, smart energy system** technology option refers to all the policies which promote the creation of a decentralised energy system in which the flexibility of the resources is exploited in an intelligent way for maximising the use of renewable sources and existing assets and reduce the energy inefficiencies [67]–[69].

The **User aggregation and LEC** technology option refer to all policies which promote the aggregation of the users and the formation of Local Energy Communities (LEC) [13], [70]–[72].

The **Power-to-X** for the energy sector encompasses all large scale conversion technologies that allow decoupling and storing electricity in other forms [73]–[75]. Power-to-heat conversion technologies are not included in this technology option since considered independently through dedicated technology options [76]. For the sake of generality, in this document, the first transformation in the X

---

[2] Biogas is a combination of two-thirds of methane (CH4) and the rest is mostly carbon dioxide (CO2) with traces of hydrogen sulphide which can be enriched to produce natural gas [46].

[3] Biofuels are fuels obtained from living organisms, from metabolic by-products, i.e., organic or food waste products, and from plants whose seeds can be used to extract oil [47].

[4] Synfuel is a liquid or gaseous fuel derived from a source such as coal, shale oil, tar sands, or biomass, used as a substitute for oil or natural gas [48]. Synthetic fuels based on hydrogen produced from renewable electricity (through water electrolysis) are fed together with CO2 into a reactor forming a synthesis gas (CO and H2) that is then liquefied and further refined to become, for example, e-diesel or e-kerosene [49].

[5] Syngas is either the mixture of nitrogen and hydrogen, the kind of mixture needed for ammonia production, or carbon monoxide/hydrogen (CO:H2) mixtures, the building blocks for the production of methanol, hydrocarbons, synthetic gasoline and diesel, or ethanol [50].

chain does not always consider hydrogen, but also other energy vectors, generally, among the various options, the X states for chemical, fuel, gas, hydrogen, liquid, and syngas. Power-to-X is meant to be utilised for freight and passenger transportation. The actual maturity level of P2X technologies makes them economically viable only in large plants. Therefore, P2X technologies are not expected to be connected to the distribution system.

The **Energy storage systems (electric, thermal, hydro)** technology option includes all devices which allow storing the energy in any form [77]–[80].

The **Nuclear power plant** technology option refers to the use of power plants fed by nuclear energy [81], [82].

The **Reserve gas sources** technology option refers to power plants fed by gas extracted from proven reserves [83], [84].

The **Renewable energy: solar, on-shore/off-shore wind, climate-neutral fuels** technology option is related to all those policies which promote the use of renewable energy sources at any scale [85], [86].

2.4 Technology options aggregation and categorisation

In this section, to ease the analysis of the national plans, the technology options defined in section 2.3 are aggregated by considering their similarity in terms of the service provided through their use. The aim is to form a concise list of univocal items to analyse the impact on the distribution network planning and operation (addressed in section 3). According to this segmentation, the technology options are grouped, as shown in Table 2-1.

The **Plug-in Electric Vehicles (PEV)** category includes all technology options that refer to electric vehicles for individual use (e.g., cars, bikes, scooters) equipped with batteries for which energy is used for mobility purposes. The BEV utilises the electric energy adsorbed from the grid for charging the onboard batteries. The power flow between the BEV and the electrical grid can be unidirectional or bidirectional, depending on the particular technology exploited. It includes the **BEV** technology option. Also, the **Plug-in Hybrid Electric Vehicles** technology option is considered part of this technology category.

The **Non-Plug-in Hybrid Vehicles** technology category includes all technology options that refer to vehicles for individual use (e.g., cars, bikes, scooters) equipped with a conventional combustion engine or an electric motor that cannot be plugged in. The HEV category includes the **FC-EV**, **Combustion engine + power-2-X**, **and biomass for long-haul transport**.

The **Traffic Flow Actions** category includes all technology options of the transportation sector focused on managing the use of the transportation infrastructure and assets. The Traffic Flow Actions category includes **multimodal transport**, **traffic interconnection and flow automation**, **shared mobility** technology options.

The **Building Structural Actions** category includes all technology options of the Building stock sector related to the policies or actions for improving the energy performances of buildings. The Building Actions category includes **Building refurbishment**, **Building standards (zero or plus energy house)**, and **Passive solutions** technology options.

The **Building Device Actions** category includes all technology options of the building sector, which refer to the installation of new devices to improve the buildings' energy performances. Some of the devices included in this category involve electrical energy whereas other devices do not; therefore, two subcategories can be devised the **Building Electric Device Actions** and the **Building Non-Electric Device Actions** subcategories. The Building Non-Electric Device Actions subcategory includes Condensing boiler and Solar water heating. The Building Electric Device Actions subcategory includes **Heat pump, CHP (non-fossil), CHP (high efficiency), Electrification of C&H demand, Renewable energy at the household level, and Building automation** solutions.

The category **Infrastructural Building Actions** for the Building stock sector includes the technology options that refer to the realisation of infrastructural measures for improving the energy performances of the buildings. The Infrastructural Building Actions category contains the creation of **Heating and cooling networks** technology option.

The **Electricity System Policy Actions** category include all the technology options that refer to policies or actions for improving the energy performances of the electricity system. The **Electricity System Actions** category contains the **decentralisation policies, the (smart) digitalisation actions, user aggregation, and LEC creation**.

The **Energy Flexibility** category comprises the **Energy storage systems** (electric, thermal, hydro) technology option and **Power-to-X**. Energy flexibility also describes the flexibility available from the adequate control of generation and demand resources mentioned in section 2.3 for the sake of simplicity; the term "flexible resources" here summarise all these technology option**s**.

The **Large Power Plant** category includes all technology options which refer to the exploitation of large power plants. It comprises technology options based on renewable energy sources (**Renewable energy: solar, on-shore/off-shore wind, climate-neutral fuels**), and nuclear or fossil fuels (**Nuclear power plants and Reserve gas sources**).

Table 2-1. Classification of the technology options

Technology Option Category	Technology option
Plug-in Electric Vehicles	Battery Electric Vehicles (BEVs)
	Plug-in Hybrid Electric Vehicles
Non-Plug-in Hybrid Vehicles	Fuel cell electric vehicles (FC-EV)
	Combustion engine + Power-to-X
	Biomass for transport
Traffic Flow Actions	Multimodal transport
	Traffic interconnection and flow automation
	Shared mobility
Building Structural Actions	Building refurbishment
	Building standards (zero or plus energy house)
	Passive solutions
Building Non-Electric Device Actions	Condensing boiler
	Solar water heating
Building Electric Device Actions	Heat pumps
	CHP (non-fossil)
	CHP (High Efficiency)
	Electrification of C&H demand
	Renewable energy at the household level
	Building automation
Infrastructural Building Actions	Heating and cooling networks
Electricity System Policy Actions	Decentralised and smart energy system
	User aggregation and LEC
Energy Flexibility	Power-to-X
	Energy storage systems (electric, thermal, hydro)
	Flexible resources (generation and demand)
Large Power Plant	Nuclear power plant
	Reserve gas sources
	Renewable energy: solar, on-shore/off-shore wind, climate-neutral fuels

2.5 Technological options in long-term EU national plans

The scale of technologies can differ significantly among different long-term scenarios, hence impacting the distribution system operation and planning. As it could not reasonably be predicted how technologies will mature technologically and economically in scenarios up to 2050, significant uncertainty for future distribution system operation and planning remains. The prominence of technology options (defined in section 2.3) in the treated national long-term strategies is identified qualitatively to support the planning activities. The prominence of a technology option or respective group in a scenario path helps to qualitatively assess the impact on the distribution system operation, planning and the respective need for flexibility.

Based on the definition of the technology options provided in section 2.3, the actions proposed in the national plans are mapped to identify the corresponding technology options. The aim is to obtain a concise list that eases the communication of the technology options included in the different long-term national plans.

2.5.1 *Comparison of long-term ambitions*

Table 2-2 resumes the 2050 ambitions mentioned in the long-term national plans of the target countries analysed in sections: 2.5.2.1 for Germany [87], 2.5.2.2 for Spain [88], 2.5.2.3 for Belgium [89], [90], 2.5.2.4 for Portugal [91], and 2.5.2.5 for Poland [92]. Considering the reference year in parenthesis, for each country in Table 2-2 specifies the long-term expectations in terms of the overall reduction of GHG emissions (column 2 - GHG emissions), the reduction of the energy use due to the energy efficiency policies (column 3 - Energy efficiency), the overall share of energy production from RES (column 4 - RES), the quota of energy consumption from renewable energy sources in the electricity (column 5 - RES-E), transportation (column 6 - RES-T), and cooling and heat sectors (column 7 - RES-C&H). For Belgium, ambitions are split according to the regional segmentation (Wallonia - W, Flanders - Fl, Brussels Capital Region - BCR).

Table 2-2. Comparison table of the long-term ambitions of the target countries

Country		GHG emissions	Energy efficiency	RES	RES-E	RES-T	RES-C&H
Germany		Up to -95% by 2050 (1990)	Not Available	100% by 2050	100% by 2050	Emission free by 2050	Emission free by 2050
Spain		-90% by 2050 (1990)	-50% by 2050 (2020)	97% by 2050	100% by 2050	-79% by 2050	-97% by 2050
Belgium	**W**	Up to -95% by 2050 (1990)	-41% by 2050 (2017)	100% by 2050	100% by 2050	Emission free by 2050	Up to 91% by 2050 (2005)
	Fl	-85% by 2050 (2005)	Not Available	Not Available	100% by 2050	Emission free by 2050	-2.3 Mt CO2eq by 2050 (2005)
	BCR	0 in 2050	Not Available	Not Available	100% by 2050	Emission free by 2050	Not Available
Portugal		Up to -90% by 2050 (2005)	Up to -47% by 2050 (2015)	+88% in consumptions by 2050 (2015)	100% by 2050	93% by 2050	+68% by 2050 (2005)
Poland		-30% (1990) by 2040	-23% (1990) by 2040	28.5% by 2040	39.7% by 2040	22% by 2040	34.4% by 2040

2.5.2 *Technology options considered in the long-term national plans*

In the following sub-chapters, the description and emphasis on technology options in the long-term national strategies are listed. In each plan, the level of development of each technology option is different. The different degrees of deployment expected for each technology option are studied to obtain a non-binary analysis. The examined plans are mainly descriptive since defining national strategic goals; therefore, a qualitative assessment is considered in terms of each plan's emphasis on each technology option. The emphasis has been deducted from the vocabulary used to describe the exploitation of each specific technology option. This means, not only the frequency of mentioning a specific technology option is considered in the qualitative assessment of emphasis, but also the overall consistency of the chapters mentioning the technology options, specifically also in the overall energy system context. The emphasis is qualitatively described according to the following three-points scale:

- **Low** - Minor emphasis
- **Medium** - Medium emphasis
- **High** - High emphasis

The lines are colour-coded based on the chapter where the main description of technology options is encountered in the analysed plans. Therefore, three sectors are considered: transportation, buildings, and energy. The presentation of the result of the analysis of the plans follows the colour scale in Table 2-3.

Table 2-3. Sector legend

Sectors
Transport sector
Building sector
Energy sector

2.5.2.1 Germany

The results of the qualitative analysis of Germany's long-term strategy, titled "Climate Action Plan 2050" [87], is shown in Table 2-4. The colour-coding presented in Table 2-3 describes the chapters where the technology options are mainly treated.

As highlighted in Table 2-2, the German plan establishes the target of reducing GHG emissions in a range between 80%-95% compared to 1990 by 2050. In terms of energy efficiency, the German plan fixes the target of achieving a virtual carbon neutral building stock, with a significant reduction of fossil use for heating and warm water. The virtual carbon neutrality target is also established for electrical energy production, which has to meet the 100% produced from renewable sources. By 2050, virtual carbon neutrality must also be achieved by the transportation and cooling and heating sectors. Table 2-4 resumes the technology options part of the Germans strategy to reach the GHG emissions objective.

Table 2-4. Technology options identified for Germany

Sector	Technology option category	Technology option	Action in the national plan	Emphasis
Transport	Plug-in Electric Vehicles	Battery Electric Vehicles	ECV/BEV	High
	Non-Plug-in Hybrid Vehicles	Fuel cell electric vehicles	FC-EV	Medium
	Non-Plug-in Hybrid Vehicles	Combustion engine + P2X	Combustion engine + P2X	Medium
	Non-Plug-in Hybrid Vehicles	Combustion engine + P2X	Power-to-X (e-fuel, syngas, hydrogen)	High
	Non-Plug-in Hybrid Vehicles	Biomass for transport	Biomass for transport	Low
	Traffic Flow Actions	Multimodal transport	Multimodal transport	Medium
	Traffic Flow Actions	Traffic interconnection and flow automation	Traffic interconnection and flow automation	Medium
	Traffic Flow Actions	Shared mobility	Car- and bike-sharing	Medium
Building	Building Electric Device Actions	Heat Pumps	Heat pumps	High
	Building Non-Electric Device Actions	Condensing boiler	Condensing boiler	Medium
	Building Structural Actions	Building refurbishment	Building refurbishment	High
	Building Structural Actions	Building standards (plus energy house)	Building standards (plus energy house)	High
	Infrastructural Building Actions	Heating and cooling networks	Heating and cooling networks	Medium
Energy	Energy flexibility	Battery Electric Vehicles (BEV)	Electrically Chargeable Vehicle (ECV)	High
	Energy flexibility	Energy storage system	Heating system storage	High
	Building device actions	Renewable energy at the household level	Renewable energy at the household level	High
	Energy system policy actions	Decentralised and smart energy systems	Smart grids and market-based flexibility	High
	Building Electric Device Actions	CHP (non-fossil)	CHP (non-fossil)	High

The results in Table 2-4 highlight Germany's emphasis on renewable energy at the household level. Moreover, the plan focuses on building refurbishment, energy efficiency, flexibility potential provided by ECV, and sector-coupling (especially with transportation).

2.5.2.2 Spain

The Spanish long-term strategy is illustrated in the document "Long-term decarbonisation strategy 2050" [88]. The result of the qualitative analysis of the Spanish strategy is shown in Table 2-5. The colour-coding in Table 2-3 is utilised for highlighting the sectors where the technology options are mainly treated.

As highlighted in Table 2-2, the Spanish plan expects to achieve climate neutrality and reduce GHG emissions by 90% from 1990 to 2050. The final energy consumption in 2050 has to be 97% covered by renewable energy sources. In particular, the electricity sector will be fed entirely by renewables, while the transportation and heating sectors have to achieve the 79% and 97% of final energy consumption from renewable energy sources by 2050, respectively. Table 2-5 resumes the technology options part of the Spanish strategy to reach the GHG emissions objective.

Table 2-5. Technology options identified for Spain

Sector	Technology option category	Technology option	Action in the national plan	Emphasis
Transport	Plug-in Electric Vehicles	Battery Electric Vehicles	ECV/BEV --> zero-emission vehicles	High
	Non-Plug-in Hybrid Vehicles	Fuel cell electric vehicles	FC-EV --> zero emission vehicles	High
	Non-Plug-in Hybrid Vehicles	Combustion engine + P2X	Power-to-X (syngas, hydrogen)	High
	Non-Plug-in Hybrid Vehicles	Biomass for transport	Renewable fuels (aviation, marine, heavy)	Medium
	Traffic Flow Actions	Multimodal transport	Change in models of mobility needs	Medium
Building	Building device actions	Renewable energy at the household level	Renewable energy at the household level	High
	Building Electric Device Actions	Heat Pumps	Heat pumps	High
	Building Non-Electric Device Actions	Condensing boiler	Condensing boiler (biofuels)	Low
	Building Structural Actions	Building refurbishment	Building refurbishment	Medium
	Building Structural Actions	Building standards (plus energy house)	Building standards (zero energy house)	High
	Infrastructural Building Actions	Heating and cooling networks	District energy concepts (renewable based)	Medium
Energy	Electricity System Policy Actions	Decentralised and smart energy system	Decentralisation, AI and interconnected energy use	Medium
	Electricity System Policy Actions	User aggregation and LEC	Own-consumption and citizen engagement: based on LEC or aggregators	High
	Electricity System Policy Actions	Decentralised and smart energy system	Smart grids: secure and flexible operation	High

As highlighted in Table 2-5, the Spanish strategy focuses mainly on customer engagement by increasing self-consumption, aggregations, and the exploitation of flexibility. The energy efficiency strategy relies on building standards oriented to zero-energy homes. The strategies for the transportation sector involve zero-emission vehicles equipped with batteries, fuel cells, and the exploitation of power-to-X solutions with syngas and hydrogen.

2.5.2.3 Belgium

The results of the qualitative analysis of Belgium's long-term strategy titled "Belgian long-term strategy" [89], [90] is shown in Table 2-6. The colour-coding in Table 2-3 is used for describing the sectors where the technology options are mainly treated.

The strategy report is provided in Dutch and French, and different measures can be described for the three regions of Belgium, Flanders (Fl)], Wallonia (W) and Brussels Capital Region (BCR), as well as for the whole country (Fed), which is indicated in Table 2-6.

As highlighted in Table 2-6, the Belgian plan expects GHG emission by 2050 reductions of non-EU ETS in the range of 85% to 87% compared to 2005 based on regional strategies. In particular, Wallonia proposes reductions in the range of 80% to 95% compared to 1990, Flanders at least 80% in non-EU ETS sectors, with expected emission reductions of 85% compared to 2005, and Brussels aims to be carbon neutral in 2050. In describing the energy efficiency objective for 2050, only Wallonia mentions energy efficiency with concrete figures stating an expected reduction of the end-user consumption from 120 TWh (in 2017) to 50 TWh (in 2050). The Belgian Federal plan, in terms of renewable energy sources, acknowledges that in each region, the total electricity production should be climate neutral by 2050. Each region aims to make its transport sector emission-free by 2050, both person cars as freight. Moreover, the expected national emission reductions in buildings range from 89% to 91% by 2050 compared to 2005. Flanders aims to reduce the total emissions of all buildings to 2,3Mt CO2eq by 2050. In Wallonia, the building sector has a high potential to contribute to emission reductions (from 90% to 100% reduction).

Table 2-2 resumes the technology options part of the Belgian strategy to reach the GHG emissions objective. The outcome of the analysis of the Belgian plan shown in Table 2-6 highlights that little emphasis is made on climate-neutral fuels and biomass, while a decentralised, demand-driven and flexible energy system are envisioned unanimously across the regions.

Table 2-6. Technology options identified for Belgium

Sector	Technology option category	Technology option	Action in the national plan	Emphasis		
				BCR	FL	W
Transport	Traffic Flow Actions	Multimodal transport		High	High	High
	Traffic Flow Actions	Multimodal transport	Modal shift to efficient passenger transport	High		
	Traffic Flow Actions	Multimodal transport	Ban on cars in city centres	High	High	High
	Plug-in Electric Vehicles	Battery Electric Vehicles (BEVs)	Shift to rail and water		High	High
	Non-Plug-in Hybrid Vehicles	Fuel cell electric vehicles	Battery-powered cars, vans, busses and lightweight vehicles		High	High
	Non-Plug-in Hybrid Vehicles	Biomass for transport	Hydrogen cars, vans, busses and lightweight vehicles		High	High
Buildings	Building Structural Actions	Building standards (zero or plus energy house)	Bio and synthetic fuels for heavy freight transport	High	High	High
	Building Structural Actions	Building Refurbishment	Building standards	High	High	High
	Building Electric Device Actions	Heat Pumps	Refurbishment (and rebuilding) of existing buildings	High	High	High
	Infrastructural Building Actions	Heating and cooling networks	Carbon neutral heat pumps	High	High	High
	Building Electric Device Actions	CHP (non-fossil)	Carbon neutral networks			Medium
	Building Structural Actions	Building standards (zero or plus energy house)	Carbon neutral biomass		Medium	Medium
	Building Structural Actions	Passive solutions	Low-environmental impact building materials and services		Medium	Medium
Energy	Building Electric Device Actions	Renewable energy at the household level	Passive cooling solutions (sunscreens, night cooling)	High	High	High
	Large Power Plant	Renewable energy	Renewable energy: solar energy	Low	High	High
	Large Power Plant	Renewable energy	Renewable energy: on-shore wind	High	High	High
	Energy Flexibility	Power-to-X	Renewable energy: offshore wind	Low	Medium	Medium
	Large Power Plant	Renewable energy	Renewable energy: climate-neutral fuels (sustainable biomass, P2X, rest streams of industrial processes)	High	High	High
	Electricity System Policy Actions	Decentralised and smart energy system	Import of renewable electricity		High	High
	Energy Flexibility	Energy storage systems (electric, thermal, hydro)	Transition to decentral, demand-driven and flexible energy system		High	High

2.5.2.4 Portugal

The results of the qualitative analysis of Portugal's long-term strategy, titled "Roadmap for Carbon Neutrality 2050 (RNC2050)" [91], is shown in Table 2-7. The colour-coding in Table 2-3 is used or describing the sectors where the technology options are mainly treated.

As highlighted in Table 2-2, the Portuguese plan establishes reducing the overall GHG emissions to 85%-90% from 2005 by 2050. In terms of energy efficiency, the target consists of reducing the primary energy consumption to 44% -47% from 2015 by 2050 and the final energy consumption has to decrease to 25%-28% from 2015 by 2050. The target for renewable energy production is to achieve by 2050 the share of 86%-88% (from 2015) of renewables in final energy consumption. By 2050, the electricity sector has to be fed virtually 100% by renewables, the transportation sector has the target to be fed for the share of 92%-93% by renewable energy sources, and the cooling and heat sector has to achieve an increase of the 66%-68% (from 2005) of renewable energy consumption. Table 2-7 resumes the technology options part of the Portuguese strategy to reach the GHG emissions objective.

Table 2-7. Technology options identified for Portugal

Sector	Technology option category	Technology option	Action in the national plan	Emphasis
Transport	Plug-in Electric Vehicles	Plug-in Hybrid Electric Vehicles	Electrification: Hybrid Vehicles	Low
	Plug-in Electric Vehicles	Battery Electric Vehicles (BEVs)	Electrification: Electrical Vehicles	Medium
	Non-Plug-in Hybrid Vehicles	Fuel cell electric vehicles (FC-EV)	Energy Vectors: H2 for heavy passenger and freight transport	High
	Traffic Flow Action	Shared mobility	Efficiency: Shared mobility	High
	Traffic Flow Actions	Traffic interconnection and flow automation	Efficiency: Autonomous vehicles	High
Buildings	Building Non-Electric Device Actions	Solar water heating	Solar water heating	Low
	Building Non-Electric Device Actions	Building standards (zero or plus energy house)	Insulation and urban rehabilitation	High
	Building Electric Device Actions	CHP (non-fossil) Electrification of C&H demand	Electrification: RES cogeneration and solar	High
Energy	Large Power Plant	Renewable energy	Centralised solar	High
	Building Electric Device Actions	Renewable energy at the household level	Decentralised solar	High
	Large Power Plant	Renewable energy	Wind (onshore, offshore)	Medium
	Large Power Plant	Renewable energy	Hydroelectric (with and without pumping)	Low
	Energy Flexibility	Energy storage systems	Storage solutions: Batteries	Medium
	Energy Flexibility	Power-to-X	Storage solutions: Hydrogen	High
	Electricity System Policy Actions	Decentralised and smart energy system	Network intelligence and flexibility	Medium
	Energy Flexibility	Power-to-X	H2 produced by electrolysis using RES (5% - 8%)	Medium

The main measures in the context of the transportation sector are the exploitation of hydrogen for heavy passenger and freight transport, the shared mobility, and the increase of the efficiency of autonomous vehicles. Moreover, the adoption of RES cogeneration and solar generation and the enhanced building insulation are of interest. Therefore, the Portugal plan points out solar and hydrogen as the main energy vectors.

2.5.2.5 Poland

The results of the qualitative analysis of Poland's long-term strategy titled "National Energy and Climate Plan" [92] is shown in Table 2-8. The colour-coding in Table 2-3 is used for describing the sectors where the technology options are mainly treated.

As highlighted in Table 2-2, the Polish plan establishes the target of reducing the overall GHG emissions by 30% by 2040 compared to 1990. The energy efficiency objective fixes the reduction of 23% of primary energy use by 2040. The exploitation of renewable sources is expected to grow by achieving 28.5% of the share of energy from renewable sources in gross final energy consumption. In the electricity sector, the share of energy from renewable resources is expected to achieve the 39.7% by 2040, in the transportation sector 22% by 2040, while 34.4% for cooling and heating by 2040. Table 2-8. resumes the technology options part of the Polish strategy to reach the GHG emissions objective.

According to Table 2-8, the Polish strategy is characterised by a great level of diversification among the different measures that can be adopted. The Polish plan envisages the exploitation of smart grids, energy communities, and market-based flexibility. The main energy resources are wind and solar, energy storage, heating plants, and CHP. As energy efficiency measures, the building refurbishment and the use of heat pumps are promoted. In the transportation sector, the main measures are the exploitation of electric vehicles and power-to-X.

Table 2-8. Technology options identified for Poland

Sector	Technology option category	Technology option	Action in the national plan	Emphasis
Transport	Plug-in Electric Vehicles	Battery Electric Vehicles (BEVs)	ECV/BEV	High
	Non-Plug-in Hybrid Vehicles	Fuel cell electric vehicles (FC-EV)	FC-EV	High
	Plug-in Electric Vehicles	Battery Electric Vehicles (BEVs)	V2G	High
	Non-Plug-in Hybrid Vehicles	Combustion engine + Power-to-X	Combustion engine + P2X/gas/biofuel/e-fuel/syngas	High
	Non-Plug-in Hybrid Vehicles	Fuel cell electric vehicles (FC-EV)	Power-to-X (hydrogen	High
	Traffic Flow Actions	Traffic interconnection and flow automation	Traffic management systems	Medium
	Traffic Flow Actions	Shared mobility	Vehicle sharing systems	Medium
Building	Building Electric Device Actions	Renewable energy at the household level	Renewable energy at the household level	High
	Building Electric Device Actions	Heat Pumps	Heat Pumps	High
	Energy Flexibility	Flexible resources (generation and demand)	BEMS with DSR option	High
	Building Structural Actions	Building refurbishment	Building refurbishment	High
	Building Structural Actions	Building standards (zero or plus energy house)	Building standards (low-energy)	High
	Building Structural Actions	Passive solutions	Spatial planning	Medium
Energy	Electricity System Policy Actions	Decentralised and smart energy system	Smart grids and market-based flexibility	High
	Electricity System Policy Actions	User aggregation and LEC	Energy communities	High
	Large Power Plant	Renewable energy	Wind onshore	High
	Large Power Plant	Renewable energy	PV	High
	Energy Flexibility	Energy storage systems	BES	High
	Energy Flexibility	Flexible resources (generation and demand)	Hybrid installation (RES technologies + storage)	High
	Large Power Plant	Nuclear power plant	Nuclear power plant	Medium
	Large Power Plant	Reserve gas sources	Reserve gas sources	High
	Large Power Plant	Renewable energy	Heating plants (biomass, biogas, geothermal)	High
	Energy Flexibility	Energy storage systems	Heating system storage	High
	Building Electric Device Actions	CHP (High Efficiency)	High-efficiency CHP	High

2.5.2.6 Collated list of technology options

The results of the analysis of the long-term strategies of the five countries relevant to the task activities are synthesised in Table 2-9. The resume of the long-term plans allows highlighting which technology options have priority and to which further analysis has to focus on identifying the impact on the distribution system. The contribution of Table 2-9 is to map the long-term national plans considering the technology option definitions in section 2.3 and harmonise the technology option terminology used in the different national plans. The colour-coding in Table 2-3 is used for describing the chapters where the technology options are mainly treated in the different national plans.

Since a qualitative analysis is addressed for each of the target countries national plans, a quantitative comparison of the outcome of the analysis of the national plan is not possible. However, having a comprehensive look at the different national plans provides high-level insight on the technology options adopted that will be adopted. This information is complemented by the analysis of the technology options included in the relevant EU long-term scenario discussed in section 4. The scenario path analysis examines the deployment level of the technology options expected for each different scenario.

However, Table 2-9 summarises the five national plans and points out similarities and differences regarding the technology options to be adopted in the future energy system of the different countries. Historical and geographical (and then climate) peculiarities influence the role that each technology option plays in the different plans. Several technology options will be developed in all countries (e.g., battery electric vehicles, heat pumps, energy efficiency measures for buildings, renewable energy at the household level, energy storage systems). While other technology options are crucial only for some of the national energy plans of countries (e.g., large renewable power plants, CHP, biomass, heating and cooling networks). These differences highlight that one solution does not fit for all countries to achieve the policy and climate goals.

Table 2-9. Collated list of technology options – Part 1 of 3 - Transport

Category	Technology options category	Technology options	Emphasis Germany	Spain	Belgium	Portugal	Poland
Transport	Plug-in Electric Vehicles	BEV	High	High	High	Medium	High
	Plug-in Electric Vehicles	Plug-in Hybrid Electric Vehicles				Low	
	Non-Plug-in Hybrid Vehicle	FC-EV	Medium	High	High	High	High
	Non-Plug-in Hybrid Vehicle	Combustion engine + Power-to-X	High	High		Low	High
	Non-Plug-in Hybrid Vehicle	Biomass for transport	Low	Medium	High		High
	Traffic Flow Actions	Multimodal transport	Medium	Medium	High		
	Traffic Flow Actions	Traffic interconnection and flow automation	Medium			High	Medium
	Traffic Flow Actions	Shared Mobility	Medium			High	Medium

Table 2-9. Collated list of technology options – Part 2 of 3 – Buildings

Category	Technology options category	Technology options	Emphasis Germany	Spain	Belgium	Portugal	Poland
Buildings	Building Electric Device Actions	Heat pumps	High	High	High		High
	Building Non-Electric Device Actions	Condensing boiler	Medium	Low			
	Building Structural Actions	Building refurbishment	High	Medium	High		High
	Building Structural Actions	Building standards (zero or plus energy house)	High	High	High	High	High
	Infrastructural Building Actions	Heating and cooling networks	Medium	Medium	High		
	Building Structural Actions	Passive solutions			Medium		Medium
	Building Electric Device Actions	Electrification of C&H demand		High		High	
	Building Electric Device Actions	Renewable energy at the household level	High	High	High	High	High
	Building Non-Electric Device Actions	Solar water heating			High	Low	

Table 2-9. Collated list of technology options – Part 3 of 3 – Energy

Category	Technology options category	Technology options	Emphasis				
			Germany	Spain	Belgium	Portugal	Poland
Energy	Building Electric Device Actions	CHP (non-fossil)	High		Medium	High	High
	Building Electric Device Actions	CHP (high efficiency)					High
	Large Power Plant	Renewable energy: solar, on-shore/off-shore wind, climate-neutral fuels			High	Medium	High
	Electricity System Policy Actions	Decentralised, flexible, smart energy system	High	High	High	Medium	High
	Energy Flexibility	Energy storage systems (electric, thermal, hydro)	High		High	Medium	High
	Energy Flexibility	Power-to-X	High		Medium	High	High
	Electricity System Policy Actions	User aggregation and LEC		High			High
	Energy Flexibility	Flexible resources (generation and demand)					High
	Large Power Plant	Nuclear power plant					Medium
	Large Power Plant	Reserve gas sources					High

3 Analysis of the technology options considering the impact on the distribution system

In this section, the technology options identified in the relevant national plans (examined in section 2.5.2) are further analysed to highlight the main features from the distribution system perspective. Furthermore, inter-dependencies and competition between technology options are identified to group individual technology options and, therefore, the combined consequences in the different scenario paths. The linkages among the technology options are qualitatively assessed. Each technology option represents a specific measure introduced to create impacts on the energy sector. However, the generated impacts may affect more than one subsector and influence the impacts and the deployment of other technology options. Finally, the technology options are assessed considering their capability to influence the electric distribution system planning and operation. The outcome of this assessment is a subset of technology options that will impact the future distribution system.

In this section, a high-level analysis considering the impacts to the distribution system is addressed. This analysis is at the system level; it assesses the technology options irrespective of local conditions, such as the actual level of deployment of the technology options and the status of the grid. This analysis aims to identify the main aspects that have to be considered in the quantitative estimation of the flexibility needs, which, in turn, requires detailed information regarding the context and knowledge of the grid. The analysis provided in this chapter concerns the impacts due to each single technology option without considering the future scenario and the actual grid characteristics; it is, therefore, scenario and grid agnostic. This section is complemented by the analysis addressed in section 4, which considers the influence of the considered future scenario.

3.1 Linkages among technology options

Each technology option represents an action introduced to create impacts on the energy sector at the country level. However, even if each technology option describes a specific measure, the generated impacts may affect more than one energy subsector and influence the impacts and the deployment expected by the other technology options. In general, the technology options can be interdependent, synergic, competing or neutral. In this section, the outcome of the qualitative analysis of the linkages among most of the technology options defined in section 2.3 is described. In the qualitative analysis, the technology options have been pairwise compared, considering a five-point scale that describes the nature and the intensity of the relationship. The five-point scale is reported in Table 3-1; it defines a cross-impact indicator used for the qualitative analysis presented in Table 3-2. Moreover, Table 3-2 shows the colour scale of the sectors to which the technology options belong (according to Table 2-3). In this section, considering the definitions in section 3, the technology options are reassigned to the sectors irrespective of the chapters of the national plans where the technology options are mainly treated. Table 3-2 is a symmetric matrix; therefore, the diagonal entries have no meaning, the diagonal entries are coloured in black.

Table 3-1. The five-points scale of the nature and intensity of the linkage between a pair of technology options

Colour scale	Nature of relationship	Description
(green)	Interdependency	Strong positive correlation between the generated impacts
(light green)	Mutual reinforcing	Positive correlation between the generated impacts
(grey)	Neutral	No influence between the generated impacts
(yellow)	Weak competition	Negative correlation between the generated impacts
(red)	Strong competition	Strong negative correlation between the generated impacts

According to the indicators described in Table 3-1, considering two generic technology options, interdependency exists if the technology options require to be both implemented for being operative. Conversely, if one of the two options is not deployed, the impacts generated by the other technology options would be negligible or non-existent. For the sake of clarity, examples of how the interaction between two technology options works are provided in the following.

Mutual reinforcing subsists when the realisation of both technology options in the couple maximises the respective effectiveness (mutually reinforcing). However, if one of the two technology options is not deployed, the deployed one preserves its ability to generate impacts.

A neutral relationship exists when the influence of one technology option on the impacts generated by the other option in the couple is negligible. Therefore, there are no interactions between the technology options under comparison.

The weak competition relationship describes two technology options that provide a similar service; however, the two technology options are not perfect substitutes; therefore, the deployment of one option limits the success or the effectiveness of the impacts generated by the other.

The strong competition relation exists when the compared technology options are perfect substitutes in terms of the service provided. In this case, the two technology options are mutually exclusive; the deployment of one of the two technology options prevent the deployment or the success of the other.

Based on the list of technology options reported in Table 2-9 defined in section 2.3 and the relationship indicators illustrated in Table 3-1, the result of the qualitative analysis of the linkage among the technology options is reported in Table 3-2. Since the sector membership is highlighted using the colour scale in Table 2-3, a qualitative bottom-up evaluation of sector coupling is also illustrated in Table 3-2.

The scope of the linkage analysis is to study the relationships among the technology options to understand the mutual influence. Since each long-term scenario devises a different level of deployment for each technology option, the influence on the other technology options has to be studied to properly assess the overall impact on the planning and operation activities of the distribution system.

However, since the scope of the activity described in this report is to identify a subset of technology options that impact the planning and operation activities of the distribution system, a detailed description of the qualitative linkage analysis in Table 3-2 is not provided. For the sake of clarity, the relationship between some pairs of technology options is explained to illustrate the used methodology. The technology options involved in the described examples are also highlighted in bold in Table 3-2.

- The BEV and FC-EV are considered strong competing technology options since both concern zero-emission vehicles. Even if they are based on different technologies, the service that is offered is the same. To illustrate, it is expected that a major diffusion of the BEV technology option limits the expansion of the FC-EV.
- BEV is considered not competing or synergic with the technology option combustion engine + Power-to-X since the latter concerns passenger and freight transport. Therefore, this technology option does not compete with BEV that mainly concern personal mobility for short and medium distance. FC-EV may compete with combustion engine + Power-to-X since both technologies can be used to power passenger and freight transport vehicles.
- Heat pumps and passive solutions for buildings are considered weakly competing technologies since both concern living comfort, but the service is provided differently. These two technology options are not interchangeable since the exploitation of passive solutions is unfeasible in every context. At the same time, the use of the heat pumps would not be the first customer choice. Therefore, the competition among heat pumps and passive solutions exists, but it is limited.
- The technology options Building automation and Heating and cooling networks are considered neither competing or interdependent technologies since the exploitation of one of

these two do not affect the penetration of the other. A building can be equipped with Building automation solutions and connected to a heating and cooling network, or it can exploit only one of these two solutions.

- Mutual reinforcing exists between the technology options BEV and Shared mobility since the deployment of car-sharing policies fosters BEV diffusion. Traditionally, the car fleet is mainly formed by cars equipped with combustion engines fed by fossil fuels. The transition towards the use of electric vehicles would be favoured by economic incentives and changes in people's mobility behaviour. The diffusion of car-sharing companies that fleet is formed by electric vehicles helps develop economies of scale in producing such cars. Therefore, the BEV is favoured. Nevertheless, the adoption of car sharing policies does not represent a necessary condition for deploying the BEV technology option.
- The technology option related to the exploitation of Renewable energy shows interdependency with the flexible asset technology option. Due to the intermittence of electricity production that characterises the majority of renewable energy sources, the introduction of flexible assets represents a measure capable of increasing the penetration of renewables in the power system. When the hosting capacity is saturated, the exploitation of the potential flexibility from the connected resource to solve the network contingencies through the provision of system services is one of the most effective solutions for increasing the capability of the power system in connecting new energy sources. Moreover, there are not relevant reasons for requiring the use of flexibility if the share of connected renewable sources does not cause grid problems.

Table 3-2. Technology options linkage analysis

Technology category	Technology options	**BEV**	**FC-EV**	**Combustion engine + Power-to-X**	Biomass for long haul transport	Multimodal transport	Traffic interconnection and flow automation	Shared Mobility	Building refurbishment	Building standards	**Passive solutions**	Condensing boiler	Solar water heating	Heat pumps	CHP (non-fossil & high efficiency)	Electrification of C&H demand	Renewable energy at the household level	**Building automation**	Heating and cooling networks	Decentralised, smart energy system	User aggregation and LEC	Power-to-X	Energy storage systems	**Flexible resources**	Nuclear power plant	Reserve gas sources	Renewable energy
Plug-in Electric Vehicles	**BEV**																										
Hybrid Electric Vehicle	**FC-EV**																										
	Combustion engine + Power-to-X																										
	Biomass for long haul transport																										
Traffic Flow Actions	Multimodal transport																										
	Traffic interconnection and flow automation																										
	Shared Mobility																										
Building Structural Actions	Building refurbishment																										
	Building standards																										
	Passive solutions																										
Building Non-Electric Device Actions	Condensing boiler																										
	Solar water heating																										
Building Electric Device Actions	**Heat pumps**																										
	CHP (non-fossil & high efficiency)																										
	Electrification of C&H demand																										
	Renewable energy at the household level																										
	Building automation																										
Infrastructural Building Actions	**Heating and cooling networks**																										
Electricity System Policy Actions	Decentralised, smart energy system																										
	User aggregation and LEC																										
Energy Flexibility	Power-to-X																										
	Energy storage systems																										
	Flexible resources																										
Large Power Plant	Nuclear power plant																										
	Reserve gas sources																										
	Renewable energy																										

3.2 Selection of technology options based on their impact on the electricity distribution system (operation and planning)

The technology options identified and categorised in section 2.3 represent the set of measures to be implemented in the next future as declared in the long-term national plan analysed in section 2.5.2. However, not all these technology options have an impact on the distribution system.

In this section, each technology option retrieved from the analysed national long-term plans (section 2.5.2) is assessed to determine if it potentially would impact the distribution system. This assessment allows identifying a subset of technology options in which the related impact can be quantified considering the level of development expected for each technology option in the different scenario paths.

The impact on the distribution system (operation and planning) is defined as the requirement of dedicated countermeasures to face the technology option deployment. A technology option can cause two impacts on the planning and on the operation stages of the distribution system:

- An impact on the operation of the power system exists when the deployment of the technology option requires countermeasures in the operating practices of the distribution system.
- A technology option impacts the planning stage of the distribution system if the presence of the technology options has to be considered in the planning (i.e. due to the reduced/increased power demand). However, no changes in the operation of the power system are expected since the technology option does not introduce a novel electricity exchange behaviour. A negative impact on the planning stage implies the need for dedicated investments and grid reinforcements.

Moreover, the impact is direct if the technology option directly affects the distribution system (i.e. it concerns connected resources), or it is indirect if the technology option affects the distribution system through the effects caused by synergic or competing technology options.

Several characteristics are considered relevant to determine if a technology option impacts distribution system planning and operation. As shown in Table 3-3, the relevant characteristics are the distribution grid connection status, the asset typology, the direction of the power flow (injection, consumption or both), and the capability to provide short-term flexibility.

- The grid connection status identifies whether a technology option does or does not represent an asset connected directly to the distribution system. Therefore, only considering the distribution network, the technology options could be grid-connected or not. Technology options connected to the distribution system can have a direct impact, while not connected technology options can only have an indirect impact.
- The asset typology characteristic is useful for categorising the technology options according to their energy behaviour. Therefore, the technology option includes generators if electrical or thermal energy is generated and injected into the electric or thermal energy systems. The load asset typology concerns technology options that consume electric or thermal energy that is therefore adsorbed from the electric or thermal energy systems. The prosumer asset typology is related to a technology option that can behave both as a generator and load. Since the resources connected to the distribution system have been traditionally loads, the knowledge of the asset typology allows understanding if the presence of the particular technology option requires changes in the operation or planning practices in case it has a generator or generation and load behaviour.
- The bidirectional electric power flow characteristic is related to the physical direction of the electric power flow determined by the technology option. Generators and loads are characterised by a unidirectional electric power flow, while prosumers have a bidirectional power flow. From the grid point of view, loads that decrease their consumption can be considered virtual power bidirectional sources. However, this interpretation is out of the scope at this point of the revision. Traditionally, the distribution system has been characterised by unidirectional power flows since the resources connected were only loads.

Nowadays, the availability of technology options that can have bidirectional power flows imposes changes to the planning and operation practices. Therefore, the information regarding the power flow direction provides relevant information for determining if the technology option can impact the distribution system planning and operation.

- The capability to provide short-term flexibility describes the ability of the technology option to adapt in a small-time interval the consumption/production behaviour according to an external signal. The technology option can be a short-term flexibility provider or not. A technology option that can provide short term flexibility can support the distribution system operation and planning. However, to exploit this flexibility, changes are required in the distribution system planning and operation practices. Therefore, it may impact the distribution system depending on the distribution grid connection status and other specific conditions.

The technology options are analysed according to their characteristics to identify whether or not an impact on the distribution system is caused.

In Table 3-3, an overview of the assessment is provided, while the expected impact for the analysed technology options is discussed in the following. The colour scale refers to the technology sector membership as defined in Table 2-3.

The **BEV** technology option impacts directly both the planning and operation stages of the distribution system. This technology option includes grid-connected assets equipped with energy storage. The electric energy is absorbed from the distribution network to be used for mobility purposes. Some technology of ECV/BEV is enabled for the vehicle-to-grid operation; therefore, the energy flow with the distribution grid is bidirectional. This technology option can provide short-term flexibility since the charging/discharging behaviour of this asset can be controlled. The ECV/BEV technology option represents a new load connected to the distribution system; it is an energy and power-intensive load that could also be controlled as a flexibility provider. In the case of V2G, it can behave injecting power to the grid as a generator. Therefore, it is expected that a large deployment of the ECV/BEV technology option impacts the planning and operation of the distribution system because its integration would require infrastructural investments and changes in the operating practices. On the other hand, it can help in the operation and planning of the system by providing flexibility.

The technology options of the **Non-Plug-in Hybrid Vehicle** and **Traffic Flow Actions categories** are considered not able to impact the distribution system since they are not grid-connected. Furthermore, even in large-scale development of these technology options, considering the business-as-usual projection of the status quo, the indirect impacts caused would be negligible. However, if fleets of vehicles used for car and bike sharing are expected to be connected to the distribution system, then the impact generated by this technology option could be not negligible.

The technology options included in the **category Building Structural Actions** can indirectly impact the distribution system's planning stage. More efficient buildings require less electric energy for cooling and heating (i.e., in the cases in which electric solutions provide these services), so the energy demand to be considered at the planning stage is lower. In any case, the actual impact on the distribution system has to be evaluated according to future scenario characteristics.

The **Building Non-Electric Device Actions technology options category** can generate indirect impacts on distribution system planning since these technology options compete with other electricity-based technologies as the same service is provided to the users. Also, in this case, the actual impact on the distribution network has to be evaluated according to the characteristics of future scenarios.

The technology options **Heat pumps, CHP (non-fossil), Electrification of C&H demand, and Renewable energy at the household level** of the **Building Electric Device Actions category** are considered able to impact the planning and operation of the distribution system directly. All these options are grid-connected and characterised by a unidirectional power flow. Depending on the particular technology exploited, Heat pumps and CHP may have a certain degree of short-term flexibility. In the case of a large deployment of these technology options, the planning and operation of the distribution system are influenced because infrastructural investments and changes in the operating practices would be required for achieving their integration. The exploitation of **Renewable energy at the household level** introduces new generators connected to the distribution system. For this reason, the large-scale deployment of this technology option will influence the planning and operation activities of the distribution system.

The **Building automation** technology option belonging to the **Building Electric Device Actions category** is considered able to generate indirect impacts on the distribution system since it depends on the relationship which would be established between automation and the energy consumed/produced by the devices controlled by the automation. Furthermore, it is relevant to account for the actual level of diffusion of the Building automation technology option in the future scenarios to be considered.

The technology option **Heating and cooling networks** of the **Infrastructural Building Actions category** impacts the distribution network planning since, considering the future scenarios, it could compete with other technology options and the distribution grid also depending on the centralised energy source and its scale, as it might be connected at the distribution level (e.g., a CHP and large-scale heat pump for a community energy system). Therefore, the Heating and cooling networks technology option influences the distribution system planning. To illustrate, depending on the particular technologies adopted, affordable cool and heat availability from dedicated networks may discourage the diffusion of standalone heat pumps. In any case, to understand if the impact is negligible or not, and in that case, to assess the extent, it is fundamental to analyse the characteristics of the future scenario.

The technology options of the **Electricity System Policy Actions category** determine a direct impact on the planning and operation activities of the distribution system since they introduce new paradigms such as decentralisation of the power system, control strategies for integrating the behaviour of the connected users, user aggregation policies. The realisation of such technology options requires structural changes that have to be considered both at the planning and operation stages of the power distribution system.

The **Energy Flexibility technology options category** represents distribution grid-connected assets characterised by a bidirectional power flow. The asset size included in this category is small or medium; only the resources connected to the distribution system are of interest. Large scale energy storage, power-to-X, and flexible demand and generation are not of interest since they could be connected directly to the transmission. Due to these aspects, the technology options regarding the Energy storage systems, the Flexible generation and demand, and Power-to-X will directly impact the distribution system planning and operation.

The technology options which form the **Large Power Plant category** are expected to determine an indirect impact on the planning activities of the distribution system. These technology options impact the distribution system indirectly since connected to the transmission grid and produce electrical energy compete with other technology options connected to the distribution grid. The deployment of these technology options is expected to generate impacts on the planning activities since operational issues at the distribution level are not expected (voltage and balancing problems generated by assets connected to the transmission system are considered to be handled at the transmission level). In general, the magnitude of the impact caused to the distribution system depends on the characteristics of the considered future scenario.

As a result of the analysis presented in Table 3-3, the subset of technology options that impact the distribution system is reported in Table 3-4.

Table 3-3. Overview of the assessment of the impact of technology options on the distribution system – part 1/2

<table>
<tr><th>Technology category</th><th>Technology options</th><th>Distribution grid-connected [Yes/No]</th><th>Asset typology [Load/generator /both]</th><th>Bidirectional electric power flow [Yes/No]</th><th>Short-term Flexibility [Yes/No]</th><th>Impact on distribution [Yes/No]</th><th>Impact stage [Planning/ Operation]</th><th>Kind of Impact [Direct/ Indirect]</th></tr>
<tr><td>PEV</td><td>BEV</td><td>Yes</td><td>Both</td><td>Yes</td><td>Yes</td><td>Yes</td><td>Both</td><td>Direct</td></tr>
<tr><td rowspan="3">NPEV</td><td>FC-EV</td><td>No[6]</td><td rowspan="3">Load</td><td rowspan="3">No</td><td rowspan="3">No</td><td rowspan="3">No</td><td rowspan="3">N/A</td><td rowspan="3">N/A</td></tr>
<tr><td>Combustion engine + Power-to-X</td><td rowspan="2">No</td></tr>
<tr><td>Biomass for long haul transport</td></tr>
<tr><td rowspan="3">Traffic Flow Actions</td><td>Multimodal transport</td><td rowspan="3">No</td><td rowspan="3">N/A</td><td rowspan="3">N/A</td><td rowspan="3">Yes</td><td rowspan="2">No</td><td rowspan="2">N/A</td><td rowspan="2">N/A</td></tr>
<tr><td>Traffic interconnection and flow automation</td></tr>
<tr><td>Shared mobility</td><td>Yes</td><td>Both</td><td>Indirect</td></tr>
<tr><td rowspan="3">Building Structural Actions</td><td>Building refurbishment</td><td rowspan="3">No</td><td rowspan="3">N/A</td><td rowspan="3">N/A</td><td rowspan="3">N/A</td><td rowspan="3">Yes</td><td rowspan="3">Planning</td><td rowspan="3">Indirect</td></tr>
<tr><td>Building standards</td></tr>
<tr><td>Passive solutions</td></tr>
<tr><td rowspan="2">Building Non-Electric Device Actions</td><td>Condensing boiler</td><td rowspan="2">No</td><td>Load</td><td rowspan="2">N/A</td><td rowspan="2">Yes</td><td rowspan="2">Yes</td><td rowspan="2">Planning</td><td rowspan="2">Indirect</td></tr>
<tr><td>Solar water heating</td><td>Generator</td></tr>
<tr><td rowspan="3">Building Electric Device Actions</td><td>Heat pumps</td><td>Yes</td><td>Load</td><td>No</td><td>Yes</td><td>Yes</td><td>Both</td><td>Direct</td></tr>
<tr><td>CHP (non-fossil)</td><td>Yes</td><td>Generator</td><td>No</td><td>Yes</td><td>Yes</td><td>Both</td><td>Direct</td></tr>
<tr><td>Renewable energy at the household level</td><td>Yes</td><td>Generator</td><td>No</td><td>No</td><td>Yes</td><td>Both</td><td>Direct</td></tr>
</table>

[6] Refuelling station equipped with small scale H2 electrolysers might be distribution grid connected [93], [94]. In principle, the impact on the distribution system of such small scale H2 electrolysers wold be comparable to the impact of BEV charging stations. However, this option is not considered in the present analysis, the actual level of maturity of this technology would require further insights to determine if small scale H2 electrolysers will be majoritarian with respect to the large scale H2 production. In this document, only large scale H2 electrolysers are considered in the analysis within the Power-to-X technology option. Large scale H2 electrolysers are not connected to the distribution grid.

Table 3-3. Overview of the assessment of the impact of technology options on the distribution system – part 2/2

<table>
<tr><th>Technology category</th><th>Technology options</th><th>Distribution grid connected [Yes/No]</th><th>Asset typology [Load/generator/ prosumers]</th><th>Bidirectional electric power flow [Yes/No]</th><th>Short-term Flexibility [Yes/No]</th><th>Impact on distribution [Yes/No]</th><th>Impact stage [Planning/ Operation]</th><th>Kind of Impact [Direct/ Indirect]</th></tr>
<tr><td>Building Electric Device Actions</td><td>Building automation</td><td>Yes</td><td>Load</td><td>No</td><td>Yes</td><td>Yes</td><td>Both</td><td>Indirect</td></tr>
<tr><td>Infrastructural Building Actions</td><td>Heating and cooling networks</td><td>No</td><td>Load</td><td>No</td><td>Yes</td><td>Yes</td><td>Both</td><td>Indirect</td></tr>
<tr><td rowspan="2">Electricity System Policy Actions</td><td>Decentralised, smart energy system</td><td rowspan="2">Yes</td><td rowspan="2">Both</td><td rowspan="2">Yes</td><td rowspan="2">Yes</td><td rowspan="2">Yes</td><td rowspan="2">Both</td><td rowspan="2">Direct</td></tr>
<tr><td>User aggregation and LEC</td></tr>
<tr><td rowspan="3">Energy Flexibility</td><td>Power-to-X</td><td>No</td><td>Load</td><td>No</td><td>Yes</td><td>No</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Energy storage systems (electric, thermal, hydro)</td><td>Yes (only small scale)</td><td>Load</td><td>Yes</td><td>Yes</td><td>Yes (only small scale)</td><td>Both</td><td>Direct</td></tr>
<tr><td>Flexible assets (generation and demand)</td><td>Yes (only small scale)</td><td>Both</td><td>Yes</td><td>Yes</td><td>Yes (only small scale)</td><td>Both</td><td>Direct</td></tr>
<tr><td rowspan="3">Large Power Plant</td><td>Nuclear power plant</td><td rowspan="3">No</td><td rowspan="3">Generator</td><td rowspan="3">No</td><td>No</td><td>No</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Reserve gas sources</td><td>Yes</td><td>No</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Renewable energy: solar, on-shore/off-shore wind, climate-neutral fuels</td><td>Yes</td><td>Yes</td><td>Both</td><td>Indirect</td></tr>
</table>

Table 3-4. Technology options that impact the distribution system in future scenarios

<table>
<tr><th>Technology category</th><th>Technology options</th><th>Impact on distribution [Yes/No]</th><th>Impact stage [Planning/ Operation]</th><th>Kind of Impact [Direct/ Indirect]</th></tr>
<tr><td>Plug-in Electric Vehicles</td><td>Battery Electric Vehicles</td><td>Yes</td><td>Both</td><td>Direct</td></tr>
<tr><td>Traffic Flow Actions</td><td>Shared mobility</td><td>Yes</td><td>Both</td><td>Indirect</td></tr>
<tr><td rowspan="3">Building Structural Actions</td><td>Building refurbishment</td><td rowspan="3">Yes</td><td rowspan="3">Planning</td><td rowspan="3">Indirect</td></tr>
<tr><td>Building standards (zero or plus energy house)</td></tr>
<tr><td>Passive solutions</td></tr>
<tr><td rowspan="2">Building Non-Electric Device Actions</td><td>Condensing boiler</td><td rowspan="2">Yes</td><td rowspan="2">Planning</td><td rowspan="2">Indirect</td></tr>
<tr><td>Solar water heating</td></tr>
<tr><td rowspan="3">Building Electric Device Actions</td><td>Heat pumps</td><td>Yes</td><td>Both</td><td>Direct</td></tr>
<tr><td>CHP (non-fossil)</td><td>Yes</td><td>Both</td><td>Direct</td></tr>
<tr><td>Renewable energy at the household level</td><td>Yes</td><td>Both</td><td>Direct</td></tr>
<tr><td>Building Electric Device Actions</td><td>Building automation</td><td>Yes</td><td>Both</td><td>Indirect</td></tr>
<tr><td>Infrastructural Building Actions</td><td>Heating and cooling networks</td><td>Yes</td><td>Both</td><td>Indirect</td></tr>
<tr><td rowspan="2">Electricity System Policy Actions</td><td>Decentralised, smart energy system</td><td rowspan="2">Yes</td><td rowspan="2">Both</td><td rowspan="2">Direct</td></tr>
<tr><td>User aggregation and LEC</td></tr>
<tr><td rowspan="3">Energy Flexibility</td><td>Energy storage systems (electric, thermal, hydro)</td><td rowspan="3">Yes (only small scale)</td><td rowspan="3">Both</td><td rowspan="3">Direct</td></tr>
<tr><td>Flexible assets (generation and demand)</td></tr>
<tr><td>Power-to-X</td></tr>
<tr><td rowspan="3">Large Power Plant</td><td>Nuclear power plant</td><td>No</td><td rowspan="3">Both</td><td rowspan="3">Indirect</td></tr>
<tr><td>Reserve gas sources</td><td>No</td></tr>
<tr><td>Renewable energy: solar, on-shore/off-shore wind, climate-neutral fuels</td><td>Yes</td></tr>
</table>

3.3 Findings of the analysis of the technology options

To overcome the existing and the expected limitations in the use of flexibility by distribution system operators, the analysis of the technology options that characterise the future electricity system represents a crucial activity.

In this document, the mid-century long-term plans of Germany, Belgium, Spain, Portugal, and Poland developed in compliance with the UNFCCC COP21 agreement are analysed to identify the technology options exploited for achieving the EU climate-neutrality goal. The analysed long-term plans show a certain degree of alignment in terms of the technology options promoted or introduced in the next future. A univocal definition for each technology option is proposed to harmonise similar technology options and provide a concise list.

The similarities and linkages of the technology options are studied. Grouping in terms of similarity allows defining categories of homogeneous technological options. The study of the linkages among the technology options identified if a pair of technology options are synergic, competing, or uncorrelated. The knowledge of the linkages among the technology options is of interest since the impact generated by the development of one technology option may affect more than one energy subsector and influence the impacts and the deployment of the other technology options. The qualitative linkage analysis highlighted which technology option pairs are synergic and which competing. This analysis serves as the basis for further activities in which the impact of the technology options will be linked with the expected degree of development considered for them in the scenario paths.

Finally, each technology option retrieved from the analysed national long-term plans is assessed to determine if its deployment would impact the distribution system. The analysis aims to build a subset of technology options in which the related impact can be quantified considering the level of development expected for each technology option in the different future scenario paths. The characteristics considered relevant to determine if a technology option impacts the distribution system planning and operation are the grid connection status, asset typology, direction of the power flow (injection, consumption, or both), and the capability to provide short-term flexibility. The assessment allowed to identify the subset of technology options that can directly or indirectly impact the future distribution system. However, to estimate each technology option's impact on the distribution system, the characteristics of the expected future scenario have to be considered. An analysis of future scenarios is performed in chapter 4.

4 Flexibility needs in long-term scenarios

4.1 Methodology adopted for the long-term scenario analysis

Identifying the impact on the distribution system caused by the deployment of the different technology options requires studying the expected future scenarios. The analysis of the expected future scenarios allows understanding the set of technology options that will be adopted and the different deployment levels expected for each technology option. Therefore, the impact on the distribution network and the corresponding need for flexibility depends on the characteristics of the future scenario considered.

The methodology adopted in this document aims to contribute to the future distribution system's flexibility needs identification, as depicted in Figure 4-1. The proposed methodology leads to the formalisation of general recommendations regarding deploying the technology option to take full advantage of the changes expected for the distribution system.

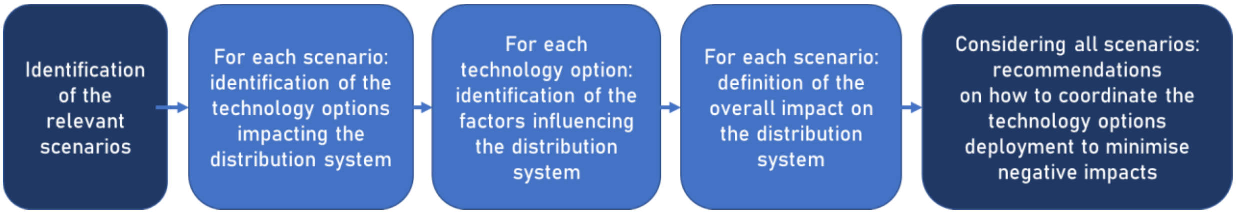


Figure 4-1. Methodology proposed for identifying the residual need for flexibility in the distribution system

The first step of the methodology in Figure 4-1 concerns the identification of the relevant future scenarios. The future scenarios of interest for the analysis are selected among the list proposed by relevant international bodies considering the possible impacts on the distribution system determined by the choices adopted. Since the high level of uncertainty of scenarios that forecast 30-50 years in the future, a high-level analysis is undertaken. Moreover, the most extreme scenarios are selected to define the boundaries of the uncertainty box.

A scenario can be considered as a portfolio of technology options; each scenario is characterised by a different level of deployment expected for each of the technology options that form that portfolio. In the second step, each selected scenario is analysed to identify the relevant technology options that can impact the distribution system in Table 3-4. Therefore, each scenario is analysed to identify the role of relevant technology options and the related level of deployment expected. Then, in the third step, the adopted methodology assesses the contribution of the relevant technology options to the distribution system flexibility needs. As described in Table 4-1, to estimate the technology options contribution on the flexibility need of the distribution system, four factors have been identified:

i. increased electricity demand at the distribution level,
ii. increased renewable generation,
iii. increased solar generation at the distribution level,
iv. increased presence of technology options that can provide flexibility to the distribution system.

In the fourth step, according to the methodology flow depicted in Figure 4-1, the identified technology options contributions are simultaneously considered to determine the impact of the scenario under analysis. In this step, the linkages among the technology options identified in Table 3-2 are relevant to understand positive and negative correlations, hence compensations or aggravation regarding the burden on the distribution system flexibility needs.

The very last step of the methodology in Figure 4-1 concerns the analysis of the results obtained by analysing all the studied scenarios. The analysis leads to recommendations regarding the measures to consider for coordinating the technology options deployment to minimise the negative impact on the distribution system and minimise the residual need for flexibility.

The technology options of interest for the scenario analysis are identified in Table 3-4 that lists the technology options that can impact the distribution system and reports the key characteristics of the corresponding impact. Therefore, each future scenario is analysed to determine which of the technology options in Table 3-4 are adopted and understand the corresponding deployment level. Then, to undertake the scenario analysis as depicted in Figure 4-1, each technology option is firstly considered independently; the related impact on the distribution system in terms of flexibility needs is studied considering the four factors:

- **Changes in the electricity demand**. It is of interest if the analysed scenario includes an electricity demand change at the distribution level and which technology options are expected to cause the electricity demand change. In fact, the load growth impacts the distribution system planning because an adequate capacity has to be guaranteed and considered when the reinforcement plans are devised. Moreover, the emergence of new loads and novel consumption habits impacts both the planning and operation of the distribution system since the typical curves of the aggregated loads lose validity. Therefore, to manage both the quantitative load growth and behavioural load change, the distribution power system may require additional flexibility resources to avoid congestions and voltage problems, shave peaks, and guarantee adequate levels of quality and security of supply.
- **Change in the electric power generation mix**. Since renewable energy sources are very often characterized by intermittent production, the increase of the electrical energy generated by renewable may increase the variability of the electrical energy production. Therefore, irrespective of the voltage level at which RESs are connected, the overall power system will require more flexibility, also at the distribution system from loads, storage, distributed generation.
- **Increase of the distributed generation.** The intermittent and non-programmable electric power generation connected at the distribution level significantly impacts the increased need for flexibility of the distribution system since the perturbances are created locally and should be solved locally to minimise the consequences for the whole power system. To illustrate, solar generation and small scale wind are promoted for buildings and industry [95]. The scenarios are analysed with a particular focus on the level of deployment expected for the distributed solar and wind generation.
- The **availability of flexible technology options** already expected in the considered scenario. Each of the scenarios of interest envisages several technology options to achieve the policy, energy, and climate goals. As pointed out in Table 3-4, some of the technology options in each scenario's portfolio can provide flexibility to the distribution system. Therefore, the deployment of such flexible technology options contributes to relieving the need for flexibility of the distribution system and, then, reducing or eliminating the residual need for flexibility in the distribution system. To illustrate, EV-charger integration in distribution increases the operational need for flexibility. However, by enabling and demanding these EV-chargers to provide flexibility (i.e., through smart charging or even V2G services), they can be a "net-zero" on flexibility needs or even "net-positive" source of flexibility.

Table 4-1 provides a brief overview of the approach used to estimate the impact of a technology option in terms of the residual need for flexibility to be connected to the distribution system. Table 4-1 describes how is assessed the impact on the flexibility needs due to a technology option. Table 4-1 is scenario agnostic, the procedure exemplified in Figure 4-1 is applied, for each scenario, for all relevant technology options. Table 4-1 shows the approach adopted for assessing the influence of a technology option on the flexibility need of the distribution system relying on the four factors previously described: the electricity demand, the generation mix, the level of distributed generation, and the availability of flexible technology options already expected in the considered scenario.

Table 4-1. Approach to estimate the impact of each technology option on the distribution system flexibility needs

Dimension	Factor	Consequence	Impact on flexibility need
Electricity demand change	Electricity demand increase	Increased burden for the distribution system	increase
Generation mix change	Increase in renewable generation	Increase energy generation variability	increase
Changes in the distributed generation	Increase of generation at the distribution level	Increased burden for the distribution system	increase
Changes in the availability of technology options able to provide flexibility	Increase of flexible technology options already expected in the scenario	Availability of options to be exploited without additional measures	decrease

4.2 Identification of relevant scenarios

The research activity described in this document focuses on the analysis of the scenario paths defined by the European Commission for the *Clean Planet for All* package [1]. The proposed scenarios have the 2050 horizon and are developed to reduce GHG emissions with respect to 1990. All proposed scenarios are focused on the total decarbonisation of the European economy, are based on the same baseline[7] and have identical technology assumptions. All scenarios assume the intensification of the development of specific technologies after 2030. The scenarios proposed by the European Commission in [1] are classified according to three categories:

1. Scenarios with GHG reductions which ambition is limiting global warming to well below 2°C;
    a. Scenarios with GHG reductions driven by decarbonised energy carriers, the ambition of well below 2°C;
    b. Scenarios with demand-driven GHG reductions, the ambition of well below 2°C;
2. Scenarios that combine the pathways of Scenario Category 1, aiming for further emissions reduction beyond the ambition of well below 2°C;
3. Scenarios with the highest GHG reductions scenarios, these scenarios are the most ambitious since they pursue limiting temperature change to 1.5°C, translated to a target of net-zero GHG emissions in 2050.

Figure 4-2 provide an overview of the relationship existing among the EU COM 773 (2018) scenarios.

[7] The baseline (known as Baseline [1]) is based on the Reference scenario 2016 (REF2016). The Baseline keeps the REF2016 macro-economic projections, fossil fuels price developments and pre-2015 Member States policies. In addition, the Baseline considers novel technology assumptions (from ASSET project) and recent updates in legislation and Commission proposals. The Baseline includes projections to 2070. The Baseline projects the achievement of energy and climate 2030 targets agreed by June 2018 and the continuation of the CO2 reduction policies. The Baseline provide the basis for comparing different long-term pathways consistent with the targets of limiting global warming to well below 2°C or 1.5°C. The Baseline does not reflect specific Member State policies adopted as of 2015.

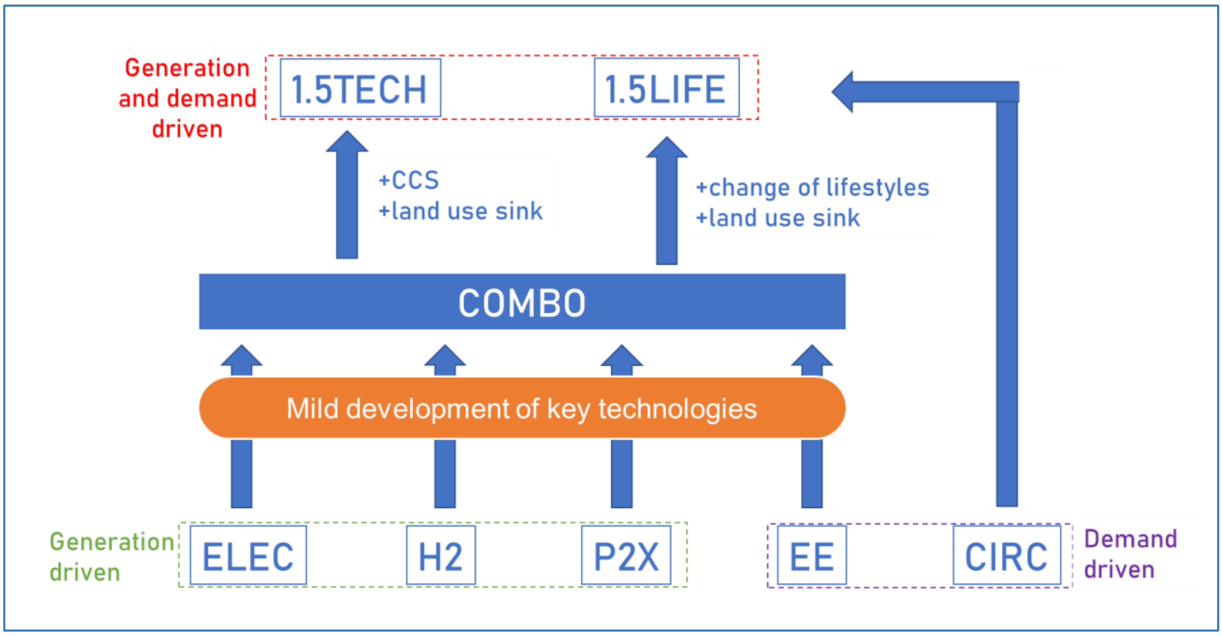


Figure 4-2. Overview of the relationship among the EU COM 773 (2018) scenarios

The EU Commission COM (2018) 773 scenarios belonging to category 1a (green) are ELEC, H2, P2X. The key action of the ELEC scenario is the electrification of energy demand and thus a higher electricity generation. The scenario H2 concern as key action the deployment of e-hydrogen in the energy demand sectors and thus hydrogen production on the supply side. Similarly, the P2X scenario is based on the deployment of e-fuels (e-gas and e-liquids, synthetic fuels produced from decarbonised electricity) in the energy demand sectors and thus e-fuels production on the supply side.

Category 1b (purple) scenarios achieve the same results as the scenarios in category 1a; however, the key action is on demand-side actions instead of generation. The key action of the EE scenario is the achievement of the highest energy efficiency in buildings, industry and transport. In comparison, the key action of the CIRC scenario is the adoption of the circular economy paradigm in the industry and, to a limited extent, in transport.

The second category of scenarios contains the scenario COMBO obtained combining solutions for each sector from the scenarios of Category 1. The COMBO scenario does not push the development of one specific technology or policy, as it happens in Category 1 scenarios, and it does not include any customer choice changes or circular economy adoption. However, the COMBO scenario preserves the global warming target of category 1; it can be considered a bridge between Category 1 and 3.

Category 3 (red) contains scenarios 1.5TECH and 1.5LIFE. Scenario 1.5TECH envisages as a key complementary action to develop negative emissions technologies as of 2050 as the land use sinks and the adoption of CCS technologies. While the 1.5LIFE concerns as the key complementary action the adoption of sustainable lifestyles such as the change in consumer choice in transport and the adoption of the circular economy in the industry.

Although each scenario highly promotes only some aspects, none of the scenarios considers an extreme development of a specific technology option. However, based on current knowledge, all scenarios consider a feasible and realistic pathway deployment for the future. The projections of all eight scenarios tend to be quite close until 2030; the differences among scenarios start becoming more visible post-2030 and in particular closer to 2050, when deployment of different energy carriers and level of demand becomes more differentiated, low carbon technology costs further reduce depending on the deployment, and the existing infrastructure is replaced or refurbished. Hence, the projections start diverging even more post-2050. The behaviour modelled considering the deployments of the scenarios and the related effects reflects the inertia of the energy system and the economy as a whole.

Table 4-2 describes the main aspects of the seven EU COM 773 (2018) scenarios [2]. For each scenario, the main drivers are the GHG 2050 target, the main common assumptions, the key actions for the power sector, industry, buildings, and transportation.

Table 4-2. Main aspects of the EU Commission COM (2018) 773 scenarios
Source: [2]

<table>
<tr><th>Scenario</th><th>Main Drivers</th><th>GHG 2050 target</th><th>Major common assumptions</th><th>Power Sector</th><th>Industry</th><th>Buildings</th><th>Transportation</th><th>Other drivers</th></tr>
<tr><td>ELEC</td><td>Electrification in all sectors</td><td rowspan="5">-80% GHG (excluding sinks) “well below 2°C” ambition</td><td rowspan="8">Higher energy efficiency post-2030.
Deployment of sustainable, advanced biofuels.
Moderate circular economy measures.
Digitalisation.
Market coordination for infrastructure deployment.
BECCS present only post-2050 in 2°C scenarios.
Significant learning by doing for low carbon technologies.
Significant improvements in the efficiency of the transport system.</td><td rowspan="8">Power is nearly decarbonised by 2050.
Strong penetration of RES facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers).
Nuclear still plays a role in the power sector and CCS deployment faces limitations.</td><td>Electrification of processes</td><td>heat pumps</td><td>Faster electrification for all transport modes</td><td></td></tr>
<tr><td>H2</td><td>Hydrogen in industry, transport and Buildings</td><td>Use of H2 in targeted applications</td><td>H2 for heating</td><td>H2 deployment for HDVs and some for LDVs</td><td>H2 in gas distribution grid</td></tr>
<tr><td>P2X</td><td>E-fuels in industry, transport and buildings</td><td>Use of e-gas in targeted applications</td><td>e-gas for heating</td><td>E-fuels deployment for all modes</td><td>E-gas in gas distribution grid</td></tr>
<tr><td>EE</td><td>Deep energy efficiency in all sectors</td><td>Reducing energy demand via Energy Efficiency</td><td>Increased renovation rates and depth</td><td>Increased modal shift</td><td></td></tr>
<tr><td>CIRC</td><td>Increased resource and material efficiency</td><td>Higher recycling rates, material substitution, circular measures</td><td>Sustainable buildings</td><td>Mobility as a service</td><td></td></tr>
<tr><td>COMBO</td><td>Cost-efficient combination of options from 2°C scenarios</td><td>-90% GHG (incl. sinks)</td><td colspan="3">Combination of most Cost-efficient options from “well below 2°C” scenarios with the targeted application (excluding CIRC)</td><td></td></tr>
<tr><td>1.5TECH</td><td>Based on COMBO with more CCS</td><td rowspan="2">-100% GHG (incl. sinks) “1.5°C” ambition</td><td colspan="3">COMBO but stronger</td><td>Limited enhancement natural sink</td></tr>
<tr><td>1.5LIFE</td><td>Based on COMBO and CIRC with lifestyle changes</td><td colspan="2">CIRC+COMBObut stronger</td><td>CIRC+COMBO but stronger + alternative air travels</td><td>Dietary changes Enhancement natural sink</td></tr>
</table>

From Table 4-2, four pillars can be identified as aspects of interest for the analysis of the scenarios and the corresponding impacts to the distribution system:

- power generation decarbonisation;
- electrification of the energy use;
- introduction of flexible resources in the power system;
- enhanced energy efficiency.

First, power generation decarbonisation is achieved by increasing the energy produced from renewable sources, nuclear generation, and CCS technologies. Second, the electrification of the energy uses regards mainly the building sector's energy demands, cooling and heating in particular. Moreover, the electrification of the energy demand of the transportation and industrial sector plays a central role. Third, the introduction of flexible resources in the power system relies on the adoption of improved operating practices (enhanced predictive management of the transmission and the distribution system), the use of energy storage devices to enable a short- and long-term energy buffer, the promotion of demand response programs to unlock the flexibility of loads and pursue the generation-following paradigm to increase hosting capacity. Finally, the achievement of an increased energy efficiency includes actions to be undertaken mainly in the industrial, building, and transportation sectors. The reduction of the energy demand of those sectors concerns the digitalisation of the processes from management, production, assembly lines, and delivery, the adoption of building automation and smart devices (e.g. smart appliances) able to optimise the energy consumption of residential and services buildings, the promotion of smart traffic management systems and multi-modal solutions to reduce the overall energy demand of mobility.

Category 1 scenarios are of interest to determine the impacts that may affect the distribution system since these scenarios are the basis for the scenarios belonging to Category 2 and 3. The Category 1 scenarios share the ambition of reducing the 80% GHG emission in 2050 and the assumptions of coordinated infrastructure deployment and significant learning by doing for low carbon technologies. The common underlying hypotheses of Category 1 scenarios are [2]:

- the adoption of 2030 as the reference year for the achievement of the most valuable results in energy efficiency and average building renovation rate;
- the adoption of digitalisation;
- the adoption of electricity consumption patterns characterised by increased self-consumption demand response;
- the development of electricity storage for RES integration;
- the adoption of moderate circular economy measures, with increased resource efficiency and improved waste management;
- the adoption of the same carbon price for all scenarios of Category 1;
- The additional electricity demand is satisfied by resources from the EU territory (mostly local onshore and offshore wind and solar, but also nuclear).

Similarities exist among the scenarios of Category 1, also considering the actions regarding renewable energy generation, traditional power generation and transport sector. Common aspects are:

- the adoption of renewable energy generation or electricity and heating & cooling;
- the increased use of advanced biofuel (and bio-methane) mandate in transport, reaching at least 25% in total transport fuels (excluding electricity and hydrogen) by 2050;
- the limited biomass imports post-2030 (close to 2015 levels, approx. 12 Mtoe).

Regarding the traditional power generation, all scenarios in Category 1 consider:

- a nearly decarbonised electric power sector by 2050,
- a not negligible role of the electricity generation using nuclear power plants,
- a limited CCS deployment until 2050.

In the transportation sector, all Category 1 scenarios consider:

- the higher intensity of policies post-2030,
- measures to increase the efficiency of the transport system (i.e. digital technologies, connected, cooperative and automated mobility, smart pricing, multi-modality and lower emission transport modes),
- ambitious CO2 standards for Light-Duty Vehicles (LDVs) and Heavy-Duty Vehicles (HDVs).

Category 1 scenarios conceive the development of sector-specific actions and technologies; therefore, the differences existing among them can be described by comparing the expected future on a sector basis. For the sake of clarity, Table 4-3 describes the main differences existing among the Category 1 scenarios pointing out the different sectors [2].

Table 4-3. Main differences among the Category 1 scenarios
Source: [2]

Scenario	Buildings	Industry	Transport	Other
ELEC	Electricity for heating	Electrification for part of high-temperature heat	Optimistic learning assumptions for batteries. Standards for cars reach 16 gCO2/km (WLTP cycle) in 2050 and become zero from 2060 onwards.	
H2	Use of carbon-neutral gases	Direct use of hydrogen in high-temperature furnaces	Optimistic learning assumptions for fuel cells. Large scale availability of H2 refuelling stations. Standards for cars reach 18 gCO2/km in 2050	Share of hydrogen in distributed gas of up to 50% in 2050 and 70% in 2070. Hydrogen production provides indirect electricity storage
P2X	Use of carbon-neutral gases		Standards for cars reach 30 gCO2/km in 2050	Share of e-gas in gas distribution grid up to 60%. E-gas production provides indirect electricity storage
EE	Renovations Improved energy efficiency in appliances	Improved energy efficiency in industrial heat applications and equipment. Waste heat Recovery	The further improved energy efficiency of vehicles. The higher model shift towards rail, waterborne transport and collective transport modes in the urban environment. Standards for cars reach 23 gCO2/km in 2050	
CIRC	High material efficiency and substitution	A circular industrial value chain, more recycling, reduced primary industrial output on average 10%. Waste heat Recovery	Integrating the sharing economy and connected, cooperative and automated mobility. More efficient logistics. Standards for cars reach 30 gCO2/km in 2050	

Considering the goal of the analysis described in this document, from the characteristics of the scenarios proposed by the EU Commission COM (2018) 773 scenarios in [2] described in Table 4-1, the Category 1 scenarios are of primary interest. In particular, the ELEC, H2, P2X, and EE are the scenarios that define the most relevant stress conditions for the distribution system. These scenarios pursue the most ambitious goal regarding the world temperature increase ("well below 2°C" ambition) and consider achieving this goal by adopting only energy generation and demand actions. Impacts determined by behavioural changes such as lifestyle changes and circular economies play a minor role. Furthermore, each of these scenarios is based on different specific drivers that determine the area to which belong the privileged technology options. The analysis of the information summarized in Table 4-3 allows establishing that the ELEC, H2, P2X, and EE represent the extremes scenarios within the actual future would probably lay. Uncertainties and specificities related to the local conditions (i.e. climate, environment, regulation, societal, and others) make it likely to assume that none of these scenarios will actually occur. However, the actual future scenario could be close to one of those scenarios that define the vertexes of the uncertainty box, as depicted in Figure 4-3, or be an average among them. Therefore, the analysis of the impacts on the distribution system determined by these scenarios can be considered to correspond to the analysis of a worst-case scenario in which multiple scenarios are of interest.

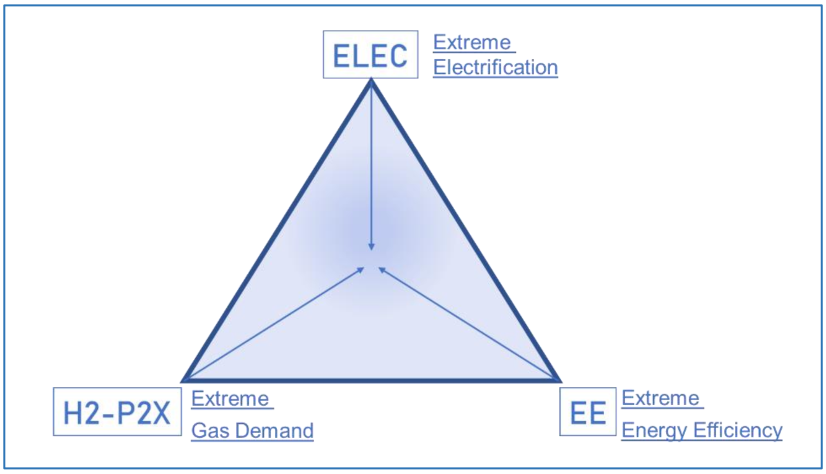


Figure 4-3. Illustrative representation of the selected scenarios

As depicted in Figure 4-3, for the scope of the analysis described in this document, the H2 and the P2X scenarios can be considered a unique scenario that considers each aspect of interest the most demanding condition for the distribution system. The H2 and the P2X scenarios are designed so that the hydrogen and the power-to-X technologies are interchangeable (i.e. the development of hydrogen technologies in H2 is equal to the development of the synfuel technologies in P2X).

4.3 Analysis of the long-term scenarios considering technology option developments

This section describes each scenario to identify the main developed technology options, assess the impact of each technology option on the distribution system, and then determine the impact associated with the entire scenario under analysis.

4.3.1 *Description of the scenarios from the technology options*

4.3.1.1 Final energy demand

Among the Category 1 scenarios of the EU Commission COM (2018) 773 [2], the ELEC scenario is the demand-driven scenario that envisages the maximum electrification of the energy demand of all sectors; the EE scenario stresses the initiatives regarding energy efficiency and the reduction of the overall energy demand; the H2 and P2X respectively consider the maximum adoption rate for the technology options based on hydrogen and the conversion of the electrical energy in other energy vectors such as hydrogen and e-fuel. In this analysis, the H2 and P2X scenarios are considered alternatively selecting each time the one that shows the highest difference with respect to EE and ELEC.

Compared to 2005, all the scenarios selected for the analysis consider a reduction in the final energy consumption, as shown in Figure 4-4. The ELEC scenario considers a reduction of the overall final energy consumption of about 35%, in which the services and the industrial sectors are expected to experience an energy demand decrease close to 23% [2]. In the transportation and residential sectors, the energy demand would decrease about 42% and 47%, respectively [2]. The H2 scenario expects the smallest reduction of the overall final energy consumption (32%); regarding the sectors of major interest for assessing the impacts on the distribution system, the reduction of the energy consumption of the residential and services sector is about 41% and 21% respectively. The EE scenario represents the most extreme scenario regarding the reduction of the overall final energy consumption. Considering all sectors, the change of the final energy consumption is about 44%. The residential sector will reduce the final energy consumption by 57%, while the services sector by 39%.

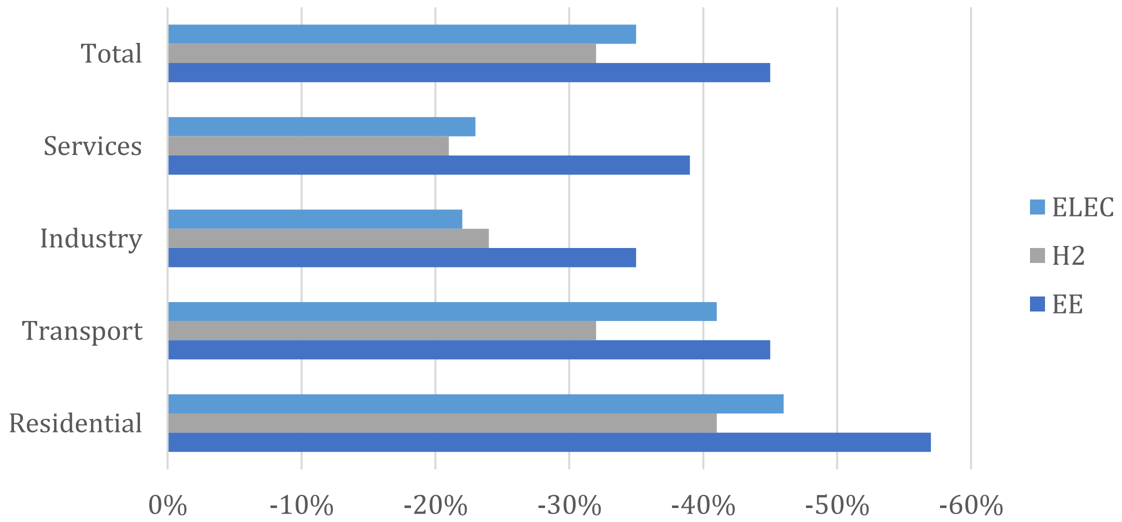


Figure 4-4. Changes in sectoral final energy consumption (% change vs 2005) Source [2]

Moreover, Figure 4-5 shows that the ELEC scenario expects that the final energy demand would reach about 800 Mtoe in 2050 [2]. The H2 scenario is characterised by a slightly higher final energy consumption with respect to ELEC; conversely, the EE scenario expects the lowest final energy consumption (about 660 Mtoe) [2].

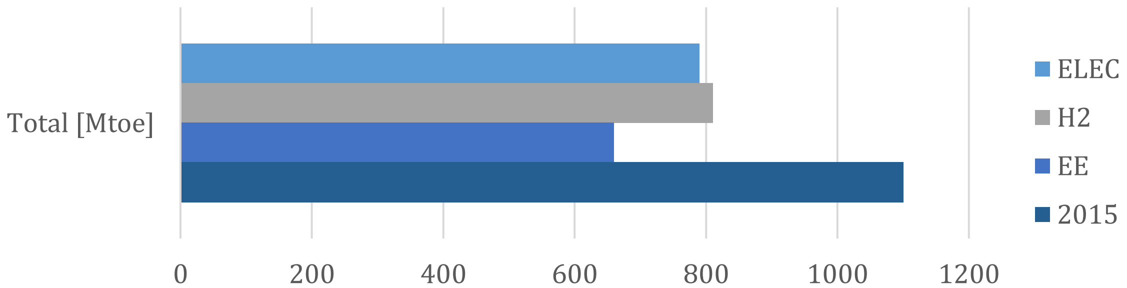


Figure 4-5. Expected final energy consumption for the considered scenarios Source [2]

Figure 4-6 depicts the share of energy carriers in final energy consumption expected in 2050 for the three analysed scenarios. In the ELEC scenario, the electricity vector will cover 53% of the final energy demand [2]. The electricity vector will cover about 40% of the final energy consumption in the H2 scenario, while about 45% in the EE scenarios. Only a negligible share of the final energy demand is expected to be satisfied by hydrogen in the ELEC and EE scenarios. However, hydrogen satisfies about 20% of the final energy consumption for the H2 scenario [2]. E-fuels replace the hydrogen quota in the P2X scenario (not represented in Figure 4-6).

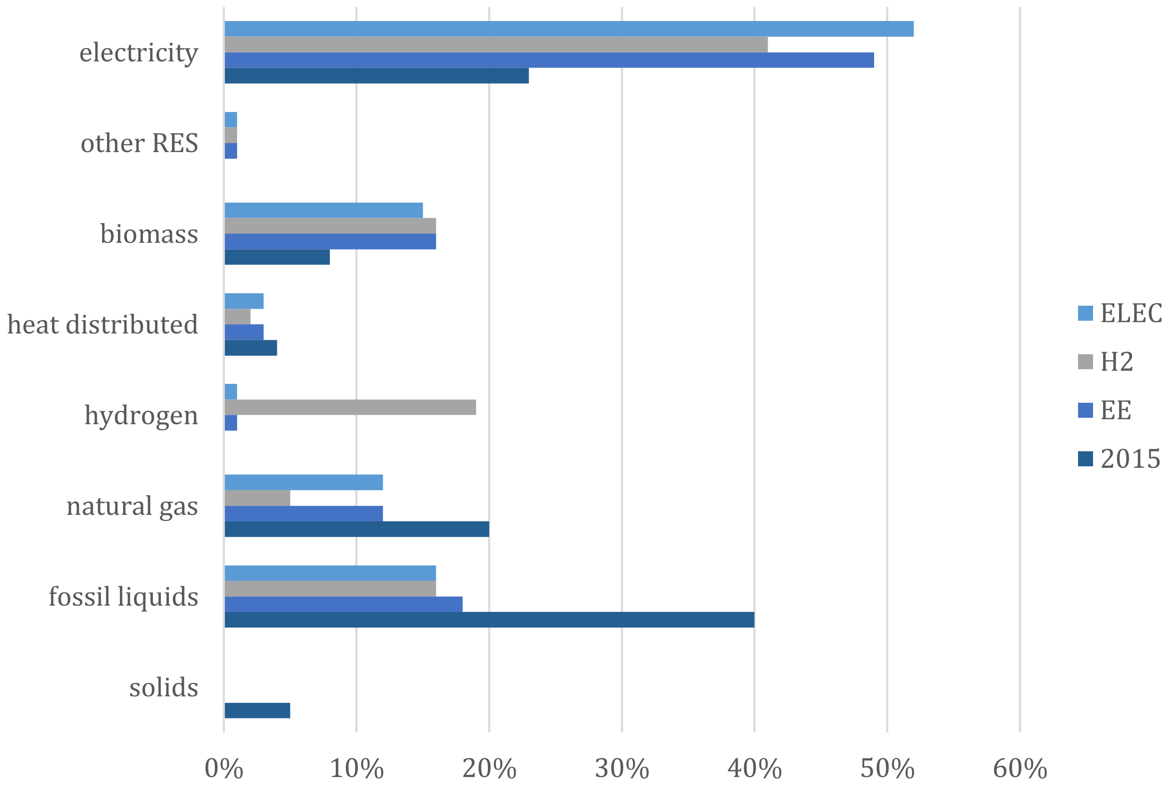


Figure 4-6. Share of energy carriers in final energy consumption
Source [2]

Figure 4-7 shows the changes in final electricity consumption in 2050 compared to 2015. Considering the electricity demand only, among the Category 1 scenarios, ELEC is characterised by the highest growth (final demand of electricity being 75% above 2015) while the EE scenario has the lowest electricity demand (36% increase with respect to 2015) due to the increased energy efficiency that counterbalances the electrification of consumers. Considering 2015 as a reference, in the ELEC scenario, in 2050, the service sector would increase by 40% the final electricity consumption; while for the residential sector, the final electricity demand would increase by about 70%. The EE scenario expects to reduce the final energy consumption of the service sector by about 3%, while the residential sector will experience a 22% growth. In the H2 scenario, the service and residential sectors will experience an increased final energy consumption of about 37% and 42%, respectively.

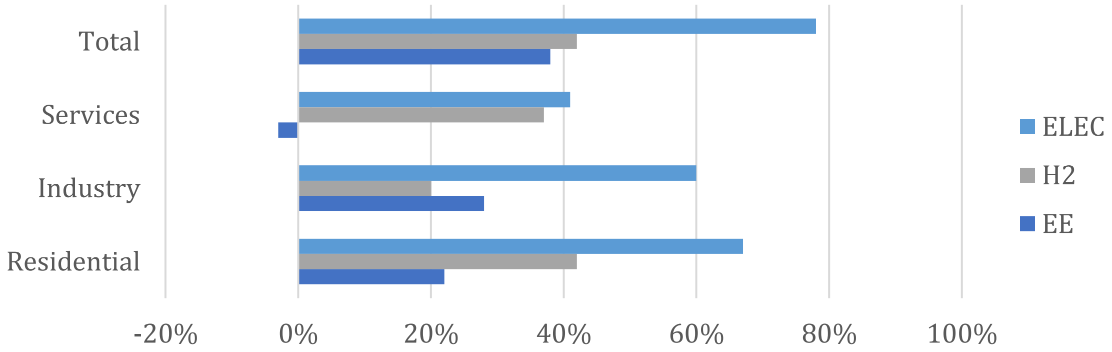


Figure 4-7. Changes in final electricity consumption in 2050 compared to 2015
Source [2]

4.3.1.2 Electric power generation

E-fuels production creates a new need for electricity supply. Consequently, the changes in the final energy demand and the production of e-fuels, the gross electricity generation in 2050 and 2070 compared to 2030 increases strongly in all scenarios but EE, as shown in Figure 4-8.

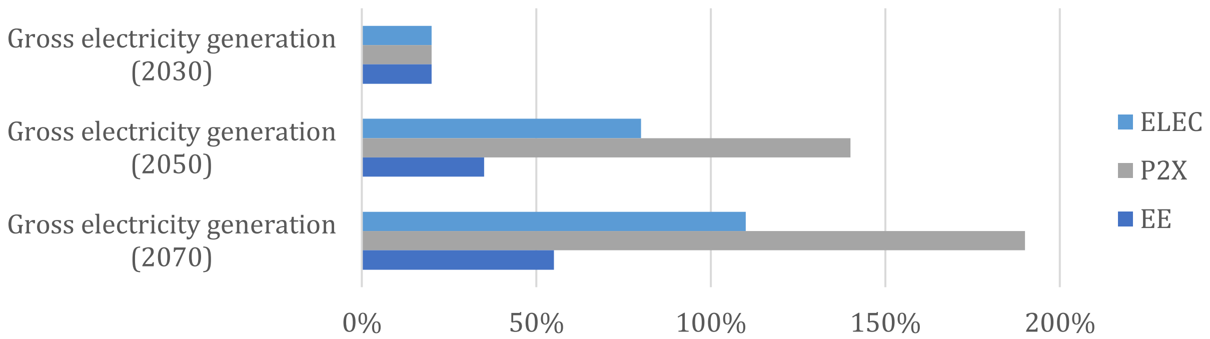


Figure 4-8. Increase in gross electricity generation compared to 2015
Source [2]

In 2050, as shown in Figure 4-9, to satisfy the increased demand for electricity, the electric power generation capacity is expected to experience a tremendous growth to achieve about 2200 GW in the ELEC scenario, which corresponds to 220% of the total installed capacity in 2015. The H2 and the EE scenarios will also experience growth of the total installed capacity, compared to 2015, the installed capacity will be 270% and 170%, respectively.

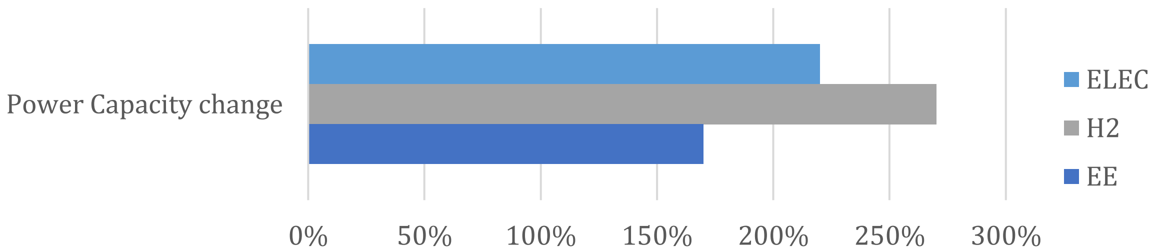


Figure 4-9. Increase of the total electric power generation capacity (reference 2015)
Source [2]

Figure 4-10 shows that the technologies considered for the analysis of the power generation capacity are solar, wind offshore, wind onshore, bioenergy with carbon capture and storage (BECCS), other renewables, fossil fuels, fossil fuels with CCS, and nuclear. In all the analysed scenarios, the main generation technologies are wind and solar. In the ELEC scenarios, these technologies together cover about 75% of the total installed capacity. Solar power plants will cover about 32% of the total installed capacity, which is about 700 GW. In H2, the share of installed solar capacity is slightly higher, whereas the EE scenario expects the lowest amount of installed solar capacity (500GW).

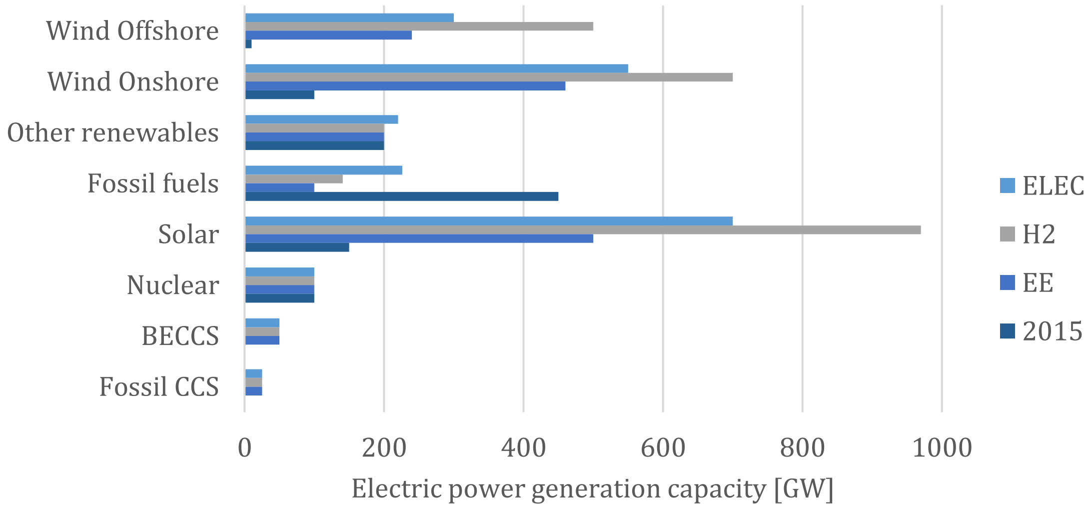
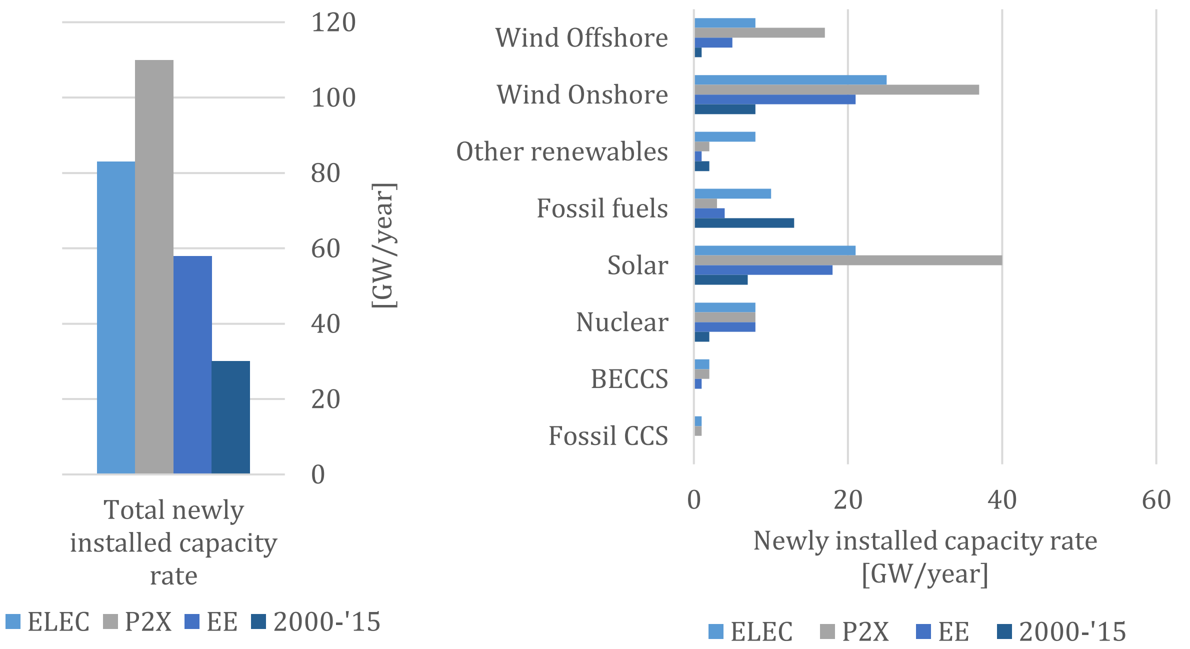


Figure 4-10. Electric power generation capacity by technology expected in 2050 Source [2]

Considering the newly installed power generation capacities, as depicted in Figure 4-11, solar generation capacity is expected to grow about 21 GW/year; it represents the 25% of the yearly increase of generation capacity in the ELEC scenario. The P2X scenario expects the highest rate of growth for the newly installed electric generation capacity. In that scenario, onshore wind and solar will cover the highest share of the newly installed generation capacity. According to its primary driver, the EE scenario has the lowest growth rate for the newly installed generation capacity. Also, in the EE scenario, the onshore wind and solar technologies are dominant.



(a) (b)

Figure 4-11. Newly installed electric power generation capacity for technology, (a) total newly installed capacity per year, (b) share of the newly installed capacity per year for each technology option
Source [2]

4.3.1.3 Energy storage

In the ELEC scenario, the volume of pumped hydro or stationary batteries electricity storage will achieve about 270 TWh in 2050. As shown in Figure 4-12, approximately less than 25% comes from pumped hydro and roughly 65% from stationary batteries. This quota of storage is to be considered in addition to the deployment of batteries vehicles. Stationary batteries would grow from 29 GW in 2030 to 178 GW (ELEC). E-fuels are deployed in the final demand sectors of the ELEC scenario. The hydrogen and e-fuel production are expected to occur in large scale plants; therefore, the related impact on the distribution system is negligible. Moreover, these energy vectors will be employed in the ELEC scenario for the transportation sector and large-scale energy storage facilities. The EE scenario expects a total storage volume of 300 TWh while the P2X scenario would achieve about 450 TWh. Batteries represent the technology that could have a more significant impact on the distribution system. Among the three scenarios, the ELEC scenario is the one that expects to install the highest share of batteries; a similar value is expected for the P2X and EE scenarios.

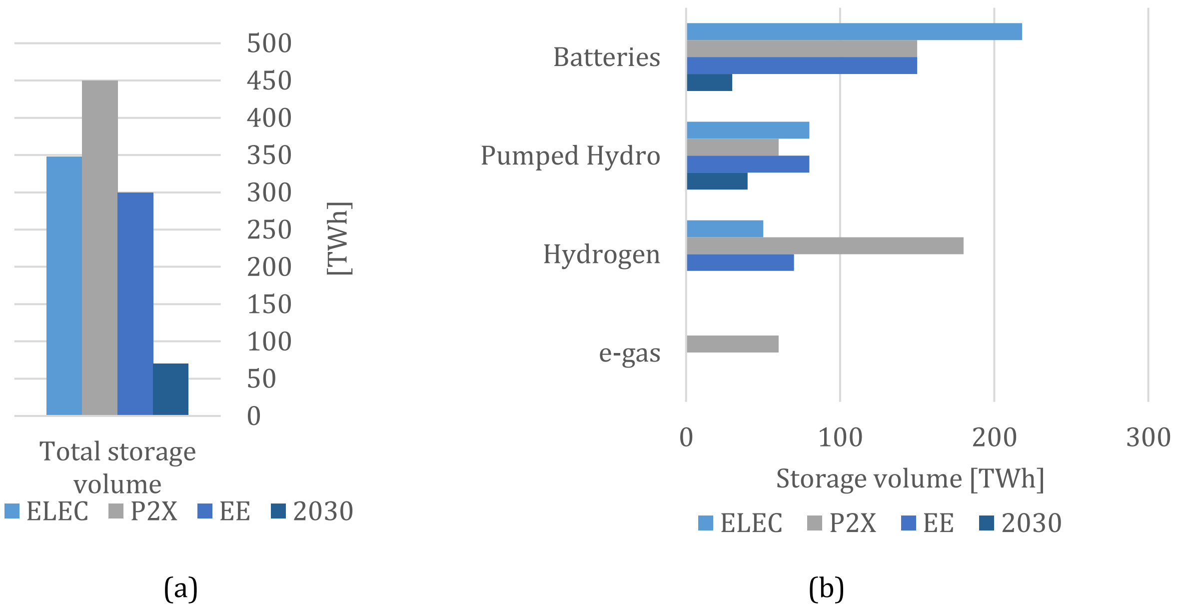


Figure 4-12. Electricity storage in 2050
(a) total volume of storage, (b) share of storage for different technologies
Source [2]

4.3.1.4 Buildings – energy efficiency

Energy consumption in buildings (residential and services) includes multiple purposes: heating & cooling, appliances, water heating, and cooking. In Europe, heating & cooling will remain the primary energy demand in European Union [2]. Currently, the most common renewable-based technologies to deliver heating and cooling services in buildings are solar thermal, geothermal, biomass boilers and ambient energy.

In general, the improvement of the thermal insulation decreases the energy consumption for cooling and heating to support fulfilling the GHG emissions objectives [2]. New buildings can be designed with high-performance thermal insulation, while old buildings can be refurbished to some extent. Nowadays, new buildings only will represent 10-25% of the buildings stock in 2050 [2]. Therefore, building refurbishing according to the energy efficiency standards will play a big role in the overall energy performance increase. It has been estimated that about the 35% of EU's buildings are older than 50 years. Moreover, all buildings built before 2010 needs partial or deep renovation to comply with the climate policies [2]. Thus, it is required to achieve a building yearly renovation rate of at least 3% [2]. Considering the scenarios under analysis, Figure 4-13 shows that the EE scenario is expected to achieve a yearly renovation rate of 1.6% for the service buildings and 1.8% for the residential buildings. The ELEC and the H2-P2X scenarios have similar yearly renovation rates of about 1.3% and 1.45% for the service and the residential sectors, respectively [2]. The yearly renovation rate in the period 2016-2030 has been equal to 1.8% for the residential sector and about the 1.4% in the service sector.

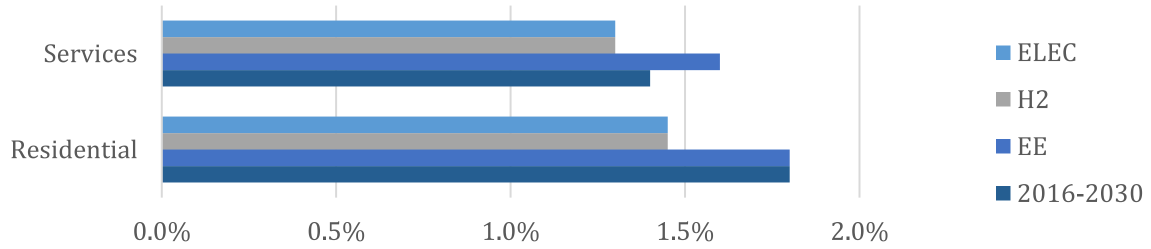


Figure 4-13. Yearly renovation rate of buildings
Source [2]

4.3.1.5 Buildings – electrification of the energy demand

Considering the actual European residential building stock, the highest share of energy consumed is for space heating, hot water production and cooling. In particular, space heating requires 71% of the overall energy consumed by buildings [2].

The technological evolution and the more stringent regulation on energy efficiency have determined considerable improvements in lighting and large appliances (e.g., refrigerators, freezers, washing machines); however, there is still room for improvements [2]. The overall EU trend is characterised by the decreasing relevance of large appliances and lighting, while the relevance of smaller appliances and devices is increasing in aggregate as their number increases and their functionality makes them more energy-intensive [2]. Furthermore, the electricity demand for air conditioning is increasing since the extremely hot weather than usual and the broader diffusion of cooling appliances [2].

The technology option that is adopted to address heating and cooling in buildings is of primary interest. The heating options show a great variety of primary energy efficiency values. Open fireplaces have a primary energy efficiency of about 30%, while the most efficient heat pumps can achieve 300% [2]. From 2010 to 2015, the average primary energy efficiency of the installed heating products raised from 60% to 66% [2]. Central space heaters are the most common heating equipment in the EU (120 million installed units in 2015) [2]. The resources are characterised by an energy input composed of fossil fuels (84%) and electricity (16%) [2]. The heaters energy consumption can be reduced by replacing condensing boilers with heat pumps combined with dedicated control units for building management. Under the current policies, it is expected by 2030 to reduce the corresponding energy consumption by about 48% in comparison to 2015. The share of electrical appliances (i.e. mainly heat pumps) will increase to 28% [2], [96].

Among the energy vectors that can be used for supplying the heat and cooling needs of buildings, geothermal energy is of interest since it is available almost everywhere in Europe. It has been estimated that about 45% of all heat demand can be covered from geothermal energy by 2050, while 25% of the population could exploit geothermal district heating and cooling [2], [97], [98].

The solar thermal adoption depends on the climate characteristic of the site in which it is installed. In Southern Europe, it represents a widely used low-cost technology for residential hot water (for example, solar thermal supplies 29% of the heating demand of the Cypriot building sector) [2]. In Central Europe, solar-heated buildings and solar district heating systems have been successfully demonstrated for detached houses and multi-family buildings.

Another relevant technology option is the High Coefficient of Performance (CoP) heat pump. These heat pumps utilise geothermal and ambient energy to produce heating and cooling. The heat pumps technology has flexible adoption since small capacity units can be used individually, while larger devices can be integrated into district heating and cooling [2]. Heat pumps cover 27% of the heating demand in the Swedish building stock, while in Finland and Italy, they cover more than 10%.

The adoption of district heating and cooling networks supports integrating various renewable heat and cooling resources while offering storage and balancing services to the electricity grid [2]. To illustrate, heat pumps installed in buildings can be integrated into low-temperature heating and cooling district networks.

Regarding the decarbonisation of the heating sector, hydrogen-based technologies have not been central in the EU [2]; however, technologies such as fuel cell micro-CHP, direct flame combustion boiler, catalytic boilers, and gas-powered heat pumps have been adopted at the international level.

Fuel cell technology is studied and tested in demonstration projects with the ambition to achieve a subsequent commercial roll-out. A relatively high investment cost characterises fuel cells; moreover, fuel cells are currently run on natural gas, so their contribution to decarbonisation is limited. In future scenarios, especially in off-grid areas, hydrogen-fuelled heating could play a bigger role [2]. Research and technology advancements on fuel cells are crucial for this technology option's role in the future energy system.

The digitalisation driver and ICT development will boost building automation technologies in the building sector. Automated buildings can adapt their operation to the occupants' needs, ensuring optimal energy performances and interacting with energy grids [2]. All the resources in the building, including heating and air-conditioning systems, can increase the overall hosting capacity of renewable energy sources, improving demand-side management while guaranteeing comfort. Moreover, building automation could lead to significant energy consumption reductions for space heating and space cooling [2]. Automated buildings are a source of flexibility for the electricity grid since they can manage the local demand and optimise the on-site energy production and storage (stationary battery and plug-in hybrid vehicles) [2].

4.3.1.6 Buildings – comparison of the ELEC, H2-P2X, and EE scenarios

In 2015, about 40% of the total final energy consumption in the EU was represented by the building demand (residential and services sectors) [2]. However, since the adoption of better building insulation and the most efficient heating system, the share of total energy consumed is expected to decrease.

As shown in Figure 4-14, in the residential sector, the energy consumption of buildings in 2050 compared to 2005 will be reduced by about 40% (ELEC, H2 scenarios) and 56% (EE scenario). The strong reduction in the EE scenario is motivated by the adoption of strong renovation policies. In all scenarios, except EE, the multiplications of consumer goods will increase the household's electrical appliances, increasing consumption. Moreover, Figure 4-14 shows that the final energy demand of buildings is expected to reduce due to the policies that will achieve noticeable results by 2030. In the ELEC and H2 scenarios, the buildings final energy demand will reduce in 2050 by about 18% compared to 2005. The residential sector will experience a reduction of about 45%, in which the energy demand of heating & cooling will be reduced by about 60%. In comparison, the energy demand for appliances and lighting will increase by about 40%. The EE scenario will achieve a total energy consumption reduction of about 60%, related to the reduction of the energy demand for heating and cooling. The energy demand for appliances and lighting will increase by about 21% in the EE scenario.

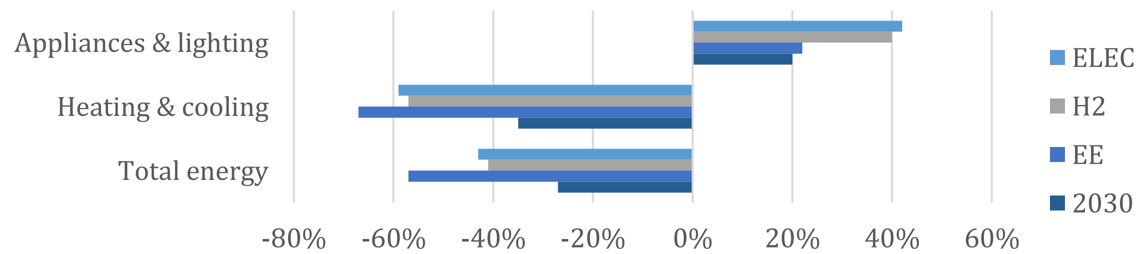


Figure 4-14. Evolution of the energy consumption in buildings in 2050 (compared to 2005) – residential sector
Source [2]

Figure 4-15 shows that considering the ELEC and H2 scenarios in terms of the effects on the services sector, the overall energy demand of buildings will decrease by about 20%, heating & cooling will reduce the energy demand by about 45%, while the appliances and lighting will increase the energy demand of about the 80%. Conversely, the EE scenario will reduce the energy consumption by about 40%, mainly related to heating and cooling.

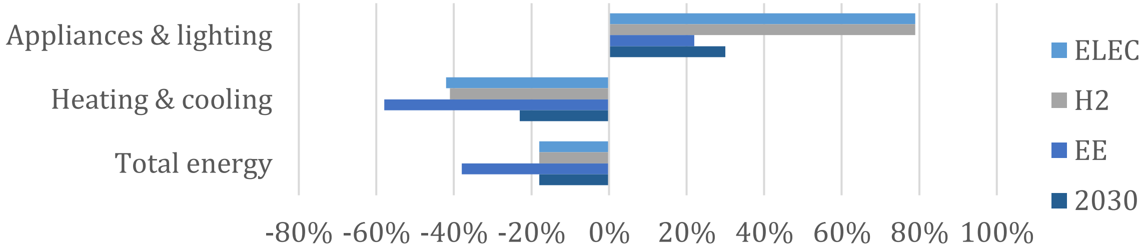


Figure 4-15. Evolution of the energy consumption in buildings in 2050 (compared to 2005) – service sector
Source [2]

In all scenarios, a similar reduction of the useful energy demand for space heating is expected [2]. This result will be achieved thanks to the increased insulation of buildings and better performing equipment. Compared to 2005, the reduction will range from 53% for the ELEC and H2-P2X scenarios to 67% in EE. Analysing the scenarios, substituting the actual energy carrier to a climate-neutral one results in the lower reduction heating & cooling needs [2].

Figure 4-16 shows that, considered the fuel mix that will feed the building sector, in the ELEC and H2 scenarios, the share of electrical energy demand will reach about 80% of the overall energy demand for the services sector. In the residential sector, the ELEC scenario expects up to 68%. In comparison, the H2 scenario will be characterised by slightly less than 60% of the share of electricity in final energy demand buildings. The EE scenario is also characterised by a share of electricity in final energy demand buildings in the service sector of about 80% and about 60% in the residential sector.

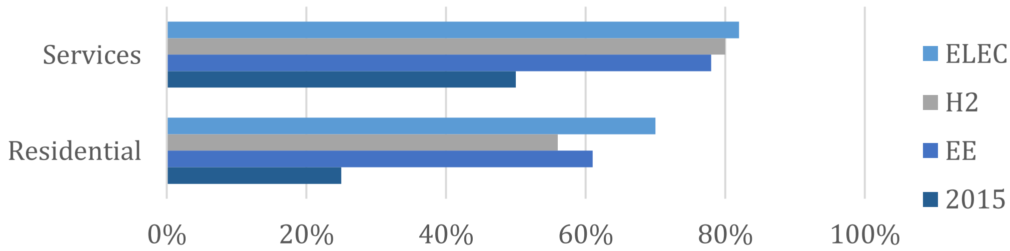


Figure 4-16. Share of electricity in final energy demand buildings
Source [2]

The main driver of the reduction of the share of electricity in final energy demand buildings is the electrification of space heating, particularly through heat pumps. The adoption of new appliances is moderated by the fact that it is assumed that the novel smart appliances are energy efficient by design. As shown in Figure 4-17, in the residential sector of the ELEC scenario, the electricity share in heating grows from 14% in 2030 to 44% by 2050. The trend is more robust in the services sector, as electricity share for space heating grows from 29% in 2030 to 60% in 2050. In the ELEC scenario, the number of dwellings adopting electrical heating systems, mainly heat pumps, is ten times bigger compared to 2015, representing some 2/3 of all dwellings. The H2 scenario has a similar trend regarding the service sector (about 50%), while in the residential sector, the share of electricity in space heating will be close to the 20%. The EE scenario has about the 40% of the share of electricity in space heating in buildings of the service sector, while this percentage in the residential sector is about the 30%.

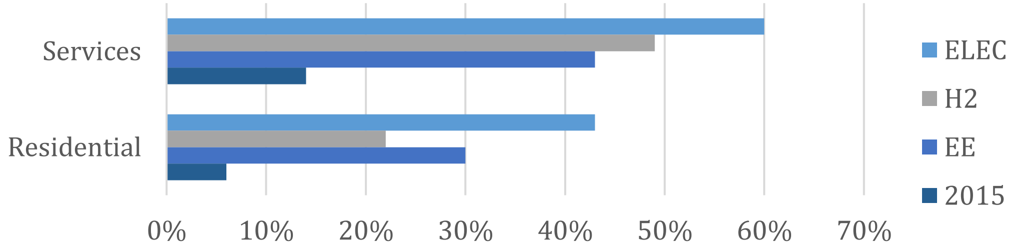


Figure 4-17. Share of electricity in space heating in buildings
Source [2]

4.3.1.7 Transport

Transport is a relevant sector for the achievements of the European Union climate goals since it represents around a third of the final energy consumption, and, traditionally, the dominant transport technologies are fed by liquid fossil fuels.

Post-2020, more stringent standards concerning the GHG emissions will be introduced for new passengers cars and vans, light and heavy-duty vehicles due to the revision of the Clean Vehicles Directive that the European Parliament has adopted and Council in June 2019 [99]. Post-2030, no further tightening of CO_2 standards is assumed since the turnover of the vehicle stock and the technological progress relies on the adoption of electric and fuel cell vehicles. Therefore, conventional internal combustion engine (ICE) vehicles that exploit diesel, gasoline, and gas, and hybrid vehicles will be gradually replaced by electrically chargeable systems (i.e. battery-electric, plug-in hybrid and fuel cell vehicles). As shown in Figure 4-18, in the long run, battery electric vehicles become increasingly important, representing the primary technology of the vehicle stock by 2050, plug-in hybrids would represent the second most widespread technology. The adoption of hydrogen vehicles depends on the availability of refuelling infrastructure and the development of hydrogen production plants, and dedicated policy incentives may be required to favour the adoption of this technology. Therefore, it is expected that fuel cell vehicles represent only a marginal share of the car's stock by 2050. The ELEC and EE scenarios concern the most extensive adoption of electric and plugin hybrid vehicles. The adoption of fuel cells is marginal in both scenarios, even if the ELEC scenario expects a higher quota. The H2 scenario is the one that expects the lower share of passengers' cars that require to be plugged in (electric and plugin hybrid). In 2050, the H2 scenario expects the large-scale availability of hydrogen stations. The 16% of car stock will be based on fuel cells, while plug-in hybrids will represent 17%, only 51% of the car stock will be based on battery electric vehicles.

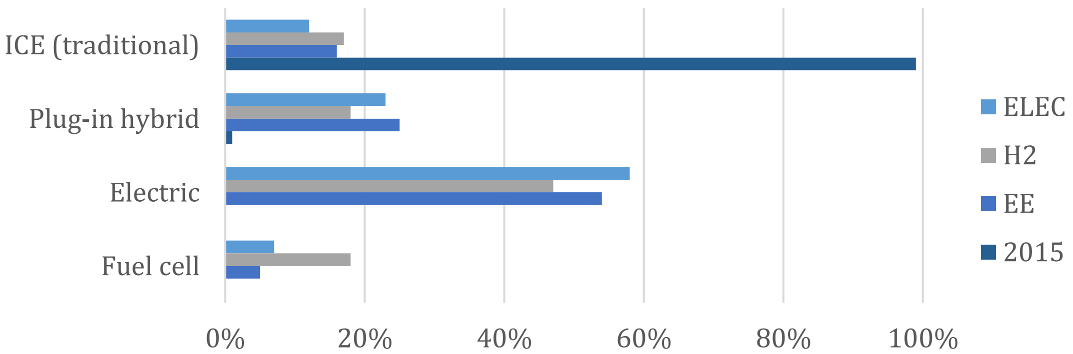


Figure 4-18. Shares in total passengers' cars stock by drivetrain technology
Source [2]

Figure 4-19 shows the shares in total light commercial vehicle stock by drivetrain technology expected in 2050 for the three scenarios under analysis and 2015. The evolution of the total light commercial vehicle stock is similar to the passengers' cars stock even if the transition towards less emissive vehicles is less massive; traditional ICE vehicles keep having a high quota. In 2015, the light commercial vehicles fleet was dominated by conventional diesel ICE. In 2050, battery-electric, plug-in hybrid and fuel cell vehicles will cover a significant share, about 80% of the total share. EE and ELEC show similar shares of the stock in 2050 (41-44% for battery electric, 22-25% for plug-in hybrids and 6-7% for fuel cells). In the H2 scenario, fuel cells will achieve up to 45% of the stock while battery-electric and plug-in hybrids represent around 19% and 16%. The H2 scenario is the one that expects the lower share of light commercial vehicles that require to be plugged in.

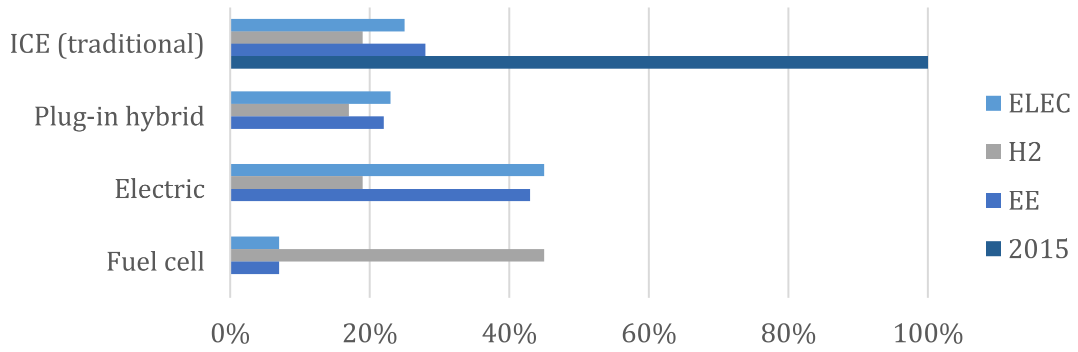


Figure 4-19. Shares in total light commercial vehicle stock by drivetrain technology Source [2]

4.4 Discussion on the long-term scenario analysis

The three selected scenarios analysed in section 4.3 highlight the similarities and differences considering the development of the main technology options identified and discussed in section 3. Quantitative and qualitative information on the scenarios has been processed considering the technology options that gain the main emphasis. Table 4-4, Table 4-5, and Table 4-6 provide the outcome of assessing the impact of each scenario on the distribution system, considering the emphasis that each scenario has on the different technology options. The assessment in Table 4-4, Table 4-5, and Table 4-6 recall the methodology described in Figure 4-1 and Table 4-1.

The distribution system needs due to the deployment of the different scenarios could be solved by resorting to infrastructure upgrading or the active management of the flexible resources. The scenarios involve by themselves the deployment of technology options able to provide flexibility to the distribution system and then, able to relieve in part the overall distribution system needs. Therefore, for the sake of simplicity, in the following section, the terminology "residual need for flexibility" is used to refer to the residual need of the distribution system for measures to address the scarcities due to the deployment of future scenarios.

4.4.1 *The ELEC scenario*

Among the three analysed scenarios, ELEC envisages the highest electrification of the final energy uses in the residential and services sector, which focus mainly on the use of electricity for heating & cooling. This aspect makes this scenario relevant for the analysis of the future distribution system. The use of renewables to feed the heating & cooling demand may resort to hybrid systems combining several types of fuels in individual buildings or decentralised district systems. The electrified heating & cooling through heat pumps is seen as an essential technology option for decarbonising the energy demand of buildings. Heat pumps are more likely to be adopted than district heating and cooling since dedicated infrastructures are not required.

Table 4-4 highlights the impact that the ELEC scenario has on the distribution system. Considering the battery electric vehicle, the impact on the distribution system is twofold: the negative impact caused by the increased demand and the positive impact due to the availability of flexible resources. However, the positive impact is conditionally obtained since it requires that smart charging or vehicle-to-grid is enabled. The level of development of battery electric vehicles shown in Figure 4-18 and Figure 4-19 allows concluding that, only considering the impact of battery electric vehicles, the ELEC and EE scenario will have a similar impact on the distribution system that is higher than the impact corresponding to the H2 scenario. Comparing the ELEC scenario with the current situation, the former will significantly impact the distribution system since battery electric vehicles are currently negligible compared to the 2050 expectations. However, the residual distribution system needs for flexibility capacity depends on smart charging and vehicle-to-grid technologies deployment. Deploying these two services is of primary interest to reduce the overall impact of the battery electric vehicle stock.

Heat pumps gain significant relevance in the ELEC scenario. In fact, the ELEC scenario is expected to exploit heat pumps for heating and cooling in most residential and service buildings. As reported in Table 4-4, heat pumps negatively impact the distribution system since it represents an additional load for the distribution system. The adoption of the heat pumps corresponds to the electrification of the cooling and heating demand that is then moved from other energy vectors to the electricity vector. However, heat pumps can positively impact the distribution system since they represent a flexible technology option. Nevertheless, this potential positive impact depends on the adoption of controls for optimising the operation of the heat pumps also considering the requirements for the distribution system operation. The control of heat pumps has to be able to adapt the heat pump operation to react to external signals and provide system services to the power system. Moreover, the amount of flexibility provided by the heat pumps increases if combined with heat storage or heating and cooling networks. Considering the information available from Figure 4-17 that represents the share of electricity used for space heating, that as explained in section 4.3 represents the energy demand from heat pumps, the ELEC scenario will have a more substantial impact on the distribution system considering the other scenarios, since the electric energy consumed for space heating is higher both in the residential and in the service sectors. Moreover, considering the status quo, the ELEC scenario will greatly impact the huge change in the electricity consumed in space heating in buildings that correspond to the massive adoption of heat pumps. Considering the flexibility introduced by the heat pumps, it is worth highlighting that the service sector has a higher potential since it is more likely to adopt automation technology and the dimension of the buildings provide more room for controlling the heat pump operation for providing flexibility to the DSO without detreating the occupants' comfort. Therefore, the overall impact on the distribution system due to the adoption of heat pumps will be higher in distribution grids that serve residential areas, while in districts devoted to the tertiary sector, the need for flexibility due to heat pumps is in part compensated by the potential flexibility of controllable heat pumps. Therefore, similar to the case of battery electric vehicles, the residual flexibility needs and the related infrastructure requirements that the distribution system may face in the ELEC scenario are reduced if the heat pumps are equipped with control systems that allow providing flexibility to the grid.

As depicted in Figure 4-13, in the ELEC scenario, the refurbishment rate of buildings will be the same as in the H2 scenario but lower than the rate of the EE scenario and the rate observed in the period 2016-2030. As highlighted in Table 4-4, refurbish buildings allows to reduce the energy demand for heating and cooling. If heating and cooling use electric energy, the higher the refurbishment rate, the lower the electricity demand, and then, the lower is the burden on the distribution grid. In the ELEC scenario, the low refurbishment rate determines a higher demand for space heating and cooling. Therefore, in the ELEC scenario, the higher demand for space heating and cooling coincides with the adoption of heat pumps, as discussed in section 4.3.1.5.

Table 4-4. Technology options analysis for the ELEC scenario

Technology option	Factor	Consequence	Impact on flexibility need	Compared to the other scenarios	Compared to the status quo
ECV/BEV	Electricity demand increase	Flexibility Demand Increase	Increase	Same impact as EE scenario. Higher impact considering H2 scenario (≈10% higher). [Reference: Figure 4-18].	High impact. [Reference: Figure 4-18].
	Increase of flexible technology options in the scenario (conditional)	Compensation of the flexibility needs, e.g. through smart charging	Decrease	Same impact as EE scenario. Higher impact considering H2 scenario (≈10% higher). [Reference: Figure 4-18].	High impact (Conditional) [Reference: Figure 4-18].
Heat pumps	Electricity demand increase	Flexibility demand increase	Increase	≈25% (H2), ≈10% (EE) higher in the residential buildings. ≈10% (H2), ≈20% (EE) higher in the service buildings. [Reference Figure 4-17]	≈45% higher in the service buildings ≈40% higher in the residential buildings. [Reference Figure 4-17]
	Increase of flexible technology options in the scenario (Conditional)	Compensation of the flexibility needs, e.g. through smart operation and additional heat-storage (Conditional)	Decrease	≈25% (H2), ≈10% (EE) higher in the residential buildings. ≈10% (H2), ≈20% (EE) higher in the service buildings. [Reference Figure 4-17]	≈45% higher in the service buildings ≈40% higher in the residential buildings. [Reference Figure 4-17]
Building Refurbishment	Decrease of the energy demand	Electricity demand decrease	Decrease	Same as H2, a smaller decrease than EE. [Reference Figure 4-13]	Lower renovation rate, hence less decrease. [Reference Figure 4-13]

4.4.2 *The H2-P2X scenario*

Table 4-5 resumes the analysis of the main technology options that impact the distribution system concerning the H2-P2X scenario. As previously described for the scenario ELEC in Table 4-5, the battery electric vehicle technology option has both a positive and negative impact on the need for flexibility of the distribution system. The H2-P2X scenarios expect a lower development of this technology option than the ELEC and EE scenarios. Therefore, the related impact on the distribution system will be lower. However, regarding the status in 2015, since currently there are almost no EVs compared to 2050 scenarios, the impact of this technology option also for the H2-P2X scenarios is considered similar to the ELEC and EE scenarios.

As described in Table 4-5, the development of heat pumps expected for the H2-P2X scenarios is the lowest in the residential sector. At the same time, it stays in between the ELEC and the EE scenarios for the service buildings. Therefore, regarding the deployment of heat pumps, the H2-P2X scenarios generate an impact on the distribution system that is expected to be lower than the impact of the ELEC scenario while slightly higher than the one of the EE scenarios. In the H2-P2X scenarios, it is expected that the heating and cooling of buildings will be addressed using other technology options (e.g., CHP, condensing boilers).

Table 4-5 and Figure 4-13 highlight that the H2-P2X scenarios will have the same refurbishment rate as the ELEC scenario. However, since the lower rate of adoption of heat pumps, it is expected that the impact on the distribution system regarding the decrease of the electrical energy demand would be lower than in the case of the ELEC scenario. Therefore, for the H2-P2X scenarios, an impact lower than the ELEC scenario is expected in terms of increased electricity demand for building space heating.

The main technology options that characterise the H2-P2X scenarios are hydrogen, e-fuels, and fuel cells. The production of hydrogen and e-fuels requires electric energy, and it could be considered as a form of energy storage. However, centralised plants for converting electric energy into hydrogen and e-fuels will not be connected to the distribution networks' final branches (Medium and Low voltage networks). Economies of scale for producing hydrogen and e-fuels require large power plants that impose their connection to the transmission or sub-transmission grids. In that case, the connection to the distribution grid would be possible only to nodes at the highest voltages and close to substations. Moreover, the typical configuration often proposed concerns plants for producing hydrogen e-fuels would be characterised by internal energy generation (i.e. coupled internally with solar and wind plants) [46], [74], [100]–[102]. However, future insight considering the technology developments and the scalability potential of decentralised systems for hydrogen production with small scale electrolysers require further investigation. More detailed scenarios that segment the hydrogen production in large- and small-scale plats are required. Considering the large-scale production predominant in the future, it is expected that the impact on the distribution system due to the large-scale generation of hydrogen and e-fuels would be minor. Fuel cells for transport are not grid-connected. Therefore, this technology option may indirectly impact the distribution system since it competes with other grid-connected technology options (e.g. battery electric vehicles) as described in Table 3-2 and Table 3-3. Estimating the impact of fuel cells requires information regarding the actual local deployment potential compared to the other competing technology options. As discussed for other technology options, local characteristics such as historical trends, availability of primary resources, and social acceptance will influence the local adoption of hydrogen-based technologies.

Table 4-5. Technology options analysis for the H2-P2X scenarios

Technology option	Factor	Consequence	Impact on flexibility need	Compared to the other scenarios	Compared to the status quo
ECV/BEV	Electricity demand increase	Flexibility Demand Increase	Increase	The lowest impact among analysed scenarios (≈10% lower). [Reference: Figure 4-18].	High impact. [Reference: Figure 4-18].
	Increase of flexible technology options in the scenario (Conditional)	Compensation of the flexibility needs, e.g. through smart charging	Decrease	The lowest impact among analysed scenarios (≈10% lower). [Reference: Figure 4-18].	High impact (Conditional). [Reference: Figure 4-18].
Heat pumps	Electricity demand increase	Flexibility demand increase	Increase	≈25% (ELEC), ≈10% (EE) lower in the residential buildings. ≈10% (ELEC) lower and ≈10% (EE) higher in the service buildings. [Reference Figure 4-17]	≈35% higher in the service buildings ≈20% higher in the residential buildings. [Reference Figure 4-17]
	Increase of flexible technology options in the scenario (Conditional)	Compensation of the flexibility needs, e.g. through smart operation and additional heat-storage (Conditional)	Decrease	≈25% (ELEC), ≈10% (EE) lower in the residential buildings. ≈10% (ELEC) lower and ≈10% (EE) higher in the service buildings. [Reference Figure 4-17]	≈35% higher in the service buildings ≈20% higher in the residential buildings. [Reference Figure 4-17]
Building Refurbishment	Decrease of the energy demand	Electricity demand decrease	Decrease	Same as ELEC, a smaller decrease than EE. [Reference Figure 4-13]	Lower renovation rate, hence less decrease. [Reference Figure 4-13]

4.4.3 *The EE scenario*

Table 4-6 resumes the analysis of the relevant technology options for the EE scenario. Considering battery electric vehicles, the EE scenario may impact the distribution system similar to the impact related to the ELEC scenario. Due to the relevance of the energy efficiency measures in the EE scenario, the energy demand of buildings is the lowest among the analysed scenarios. Therefore, considering the share of electricity for heating buildings and the expected highest refurbishment rate for buildings, it is expected that the EE scenario will produce a lower impact on the distribution system. However, considering the status quo, this impact is not negligible and have to be considered at the local level in quantitative analyses.

Table 4-6. Technology options analysis for the EE scenario

Technology option	Factor	Consequence	Impact on flexibility need	Compared to the other scenarios	Compared to the status quo
ECV/BEV	Electricity demand increase	Flexibility Demand Increase	Increase	Similar to the ELEC scenario. Higher than the H2 scenario (≈10% lower). [Reference: Figure 4-18].	High impact. [Reference: Figure 4-18].
	Increase of flexible technology options in the scenario (Conditional)	Compensation of the flexibility needs, e.g. through smart charging	Decrease	Similar to the ELEC scenario. Higher than the H2 scenario (≈10% lower). [Reference: Figure 4-18].	High impact (Conditional). [Reference: Figure 4-18].
Heat Pumps	Electricity demand increase	Flexibility demand increase	Increase	≈15% (ELEC) lower, ≈10% (H2) higher in the residential buildings. ≈20% (ELEC), ≈10% (EE) lower in the service buildings. [Reference Figure 4-17]	≈30% higher in the service buildings ≈15% higher in the residential buildings. [Reference Figure 4-17]
	Increase of flexible technology options in the scenario (Conditional)	Compensation of the flexibility needs, e.g. through smart operation and additional heat-storage (Conditional)	Decrease	≈15% (ELEC) lower, ≈10% (H2) higher in the residential buildings. ≈20% (ELEC), ≈10% (EE) lower in the service buildings. [Reference Figure 4-17]	≈30% higher in the service buildings ≈15% higher in the residential buildings. [Reference Figure 4-17]
Building Refurbishment	Decrease of the energy demand	Electricity demand decrease	Decrease	The highest decrease. [Reference Figure 4-13]	Higher renovation rate, hence. positive impact. [Reference Figure 4-13]

4.4.4 *Concluding remarks on long-term scenario analysis*

The increase of renewable generation at the household level is one of the relevant technology options for the analysed scenarios. As already discussed in section 4.3, it is expected that renewable energy generation at the household level will be characterised mainly by solar. However, considering the generation technologies developed within each scenario, only power system-wide aggregated information is available, as depicted in Figure 4-10 and Figure 4-11. The lack of information that split the quota of solar installed capacity between the transmission and distribution system does not allow further analysis of the expected impact of this technology option on the distribution system.

Among the relevant technology options, the development of CHP represents a source of flexibility for the distribution system. The combined generation of heat and power allows reducing the electric energy supply from the grid (especially for heating), and if adequately managed, provide flexibility to the DSO. However, no detailed information is available regarding the differentiation of the deployment level of these technology options in the analysed scenarios; therefore, this gap prevents determining the expected impact on the distribution system related to these scenarios.

Similarly to CHP, building automation may represent a source of flexibility for the distribution system. The deployment of building automation technology relieves the need for flexibility in the distribution system. The promotion of building automation is expected for all analysed scenarios; however, no information is available to distinguish among them. Even if some hypothesis related to the yearly renovation rate of the building can be formulated, the lack of dedicated information does not allow to devise reliable qualitative estimations.

Therefore, to estimate the impacts that the technology options have on the distribution system according to the different decarbonising scenarios is of utmost interest to improve the information available for scenarios proposed for the European Union in [2], particularly by estimating the quota of solar generation expected to be connected in the distribution system, the deployment of CHP, and the adoption of building automation technologies. It is recognised that reliable information on these technology options can be available only at the local level; however, this is in line with the requirement for moving from a high-level to quantitative estimation of the impact of the distribution system.

In conclusion, the future scenarios based on electrification, like ELEC, will create the highest-burden for the distribution system need of flexibility, while scenarios that are mainly based on energy efficiency measures (like EE) or hydrogen (H2) and P2X technologies will determine a lower need for flexibility in the power system. Figure 4-20 depicts qualitatively the impact generated to the distribution system considering the three technology options as in Table 4-4, Table 4-5, and Table 4-6, having as reference the current situation.

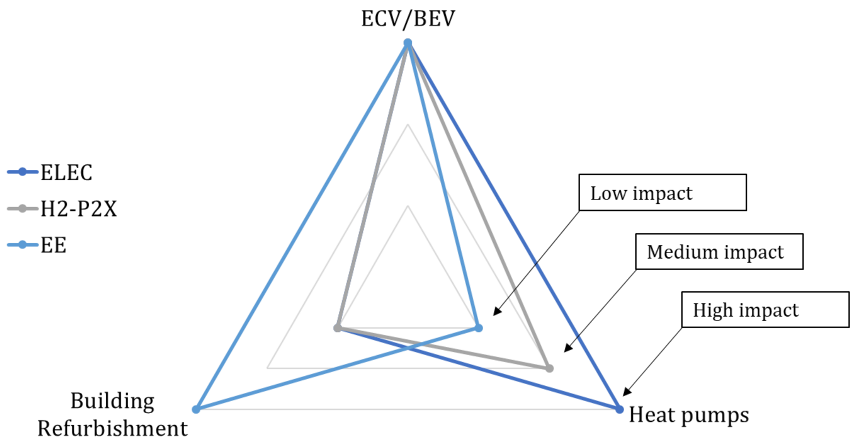


Figure 4-20. Qualitative impact of the scenarios ELEC, H2-P2X, EE considering the deployment of the relevant technology options with respect to the current situation

5 Challenges and recommendations concerning the future distribution system

The description of the EU long-term vision for climate and energy and the analysis of the long-term national plans provided in section 2, besides the analysis of the technology options (in section 3) and the analysis of the scenarios (in section 4), allow to puzzle out the main features that will characterise the long-term backdrop of the future of the distribution system. Based on the analysis of the information in previous chapters of this document, in this section, the main findings are highlighted; furthermore, challenges concerning the future distribution system are discussed and recommendations to address these challenges are provided. This section focuses on the consequences due to the deployment of the technology options, the required changes in planning and operation practices, the adoption of mechanisms for flexibility procurement, the required changes in regulation, and the business models of the main distribution system actors.

5.1 Discussion on the future deployment of the technology options

The information available on the analysed scenarios allows identifying the main technology options and the related level of deployment. The analysis described in this report identified the technology options to which carefully take into account (Table 3-4), how these technology options are intertwined (Table 3-2), and how the deployment of the different policy perspectives for the energy system of the future influence the technology option deployment and the related impact on the distribution system (Table 4-4, Table 4-5, Table 4-6). The main findings, challenges, and recommendations related to the future deployment of the technology options are resumed in Table 5-1.

Moreover, this activity allowed to identify the gaps in the scenario definition that have to be filled with local information when the residual need for flexibility for the distribution system is appraised quantitatively (e.g., the actual share of distributed generation, actual electricity demand, flexible technology options already connected to the grid). In fact, since the characteristics of the distribution system are highly dependent on the local conditions (e.g., regulation at country level, load and generation type, capacity, and volume in the area of interest, the initial status of the network), quantitative appraisals of **the future need for flexibility require the availability of local information** [103]. The analysis of the impacts on the future distribution system requires identifying the grid area under analysis (e.g., the actual level of stress, resources available, required reinforcement), the technology options that will be adopted, and estimating the corresponding level of deployment. Depending on their characteristics, the technology options can compensate for their impact on the distribution system. The remaining residual need for flexibility has to be addressed by locally promoting generation and demand flexibility. The relevance of the grid area and the context of the need have also been highlighted in EUniversal D5.1 [103].

Overall, scenario analysis highlights that the main achievements in terms of increased energy efficiency and reduced GHG emissions are achieved if the most inefficient segments are replaced with more efficient and climate-friendly technologies. However, **one solution does not fit all** due to the influence of the local conditions in terms of climate, actual status, policy goals, availability of resources, and expertise. This statement gains particular evidence considering the technology options that can be exploited for switching from fossil fuels to carbon-neutral energy vectors. For example, the future scenario design requires considering the optimal heating and cooling supply option based on the specific local circumstances, renewable resources availability, existing or feasible energy infrastructures, existing or expected buildings characteristics, and the links with the other energy systems. In some regions, heat pumps and the electrification of heating and cooling of buildings represent the optimal solution. However, in some other regions, the use of renewables alone or in hybrid systems and the development of decentralised district systems can represent the most convenient option. In particular, despite the efficiency of district heating and cooling networks [2], the realisation of such infrastructure requires considerable investments that make this technology option not everywhere viable. However, technology advancements that combine district heating and cooling network with heat pumps and CHP could represent a game-changer in some local contexts.

The scenario analysis described in this document highlights that, **compared to the current situation, irrespective of the specific high-level scenario considered, the expected deployment of distributed generation from renewables and the electrification of demand will determine relevant impacts to the distribution system**. The increased electricity generation from renewables and the increased demand at the distribution level require special attention to maximise the potential flexibility and reduce the overall net impact. Along with the electrification of the car stock and the heating and cooling of buildings, monitoring and control systems able to communicate with the DSO are needed. Estimating the flexibility required by a specific distribution grid depends on the network capacity initially available, the expected changes in terms of load and generation peaks, and the probability of occurrence of extreme events. Development plans based on scenarios exploiting mainly energy efficiency, hydrogen, and e-fuel technology will have a lower impact on the distribution systems. However, the analysis of all high-level scenarios reveals that the technology options based on electrification have a level of development such that 2050 will be tremendously different from the current situation. Therefore, the same recommendations made for the electrification-based scenario preserve their validity. Hence, the smart energy system integration across sectors has to be pursued as a primary goal in each decarbonised scenario.

Considering all scenarios described in section 4.3, in 2050, the European electricity generation mix will be drastically different from now. The electrical energy will be generated by fossil fuels (natural gas mainly) only for the share in the range between 1% and 5%. Renewables will produce more than 81% of the electricity; in particular, wind and solar will contribute to about 70% of the overall electric energy production. Nuclear power plants will generate about 10% of the electrical energy produced in 2050. Among renewable energy sources, wind power plants are the dominant technologies; in 2050, wind generation will represent 51-56% of the power production in all considered scenarios. Solar grows up to 15-16% in 2050 in all scenarios, from 3% in 2015. The massive increase of the electric energy produced using the solar source impacts the distribution system mainly for the quota of solar generators of small size connected to the distribution grids; this quota is mainly related to households and collectives [104]. Distributed wind power may be mainly adopted by micro and small enterprises and collectives [104]. Therefore, to assess the impact on the future distribution system considering the EU decarbonised scenarios, it is of utmost interest to **determine the quota of the renewable generation expected to be connected at the distribution system level**. However, the numerical value quota and the technology adopted can differ from site to site; therefore, **dedicated studies that consider the local conditions** would fill that gap and **estimate the share of renewables connected to a specific distribution system area**. Historical data and other information coming from local policy objectives regulation can be used to define the breakdown of the renewable capacity growth at the distribution system level [105].

Irrespective of the power system level at which the renewable generation is connected, the production of the largest share of electric energy from renewables requires the adoption of **storage systems** based on multiple technologies (e.g., pumped-hydro, stationary and mobile batteries, hydrogen and e-fuels) and **demand-side response programs**, as pointed out in Figure 4-12. It is expected that in 2050 the electrical energy yearly stored increases in all scenarios by about ten times in comparison to 2015. Moreover, all analysed scenarios envisage, even if with different shares, the electrification of the final consumers in the different sectors (e.g., residential, services, transport, industry). Electrification is considered an effective measure to decarbonise sectors that largely use fossil fuels. However, together with renewable electric energy generation, the electrification of final energy uses represents another driver to develop storage technologies to supply inflexible loads. Batteries based on chemical technologies are already well developed [2]; however, the future low-carbon economy will require further technological and industrial improvements in the entire value chain. Performance of batteries have to improve and, in parallel, the related costs have to reduce to allow widespread adoption of this technology option in the distribution system. In addition to the stationary storage, **battery electric vehicles represent a relevant resource capable of providing**

energy and power flexibility to the power system, particularly at the distribution system level. However, to foster the wide adoption of these vehicles, lower battery prices and advancements in energy storage technologies are necessary. Moreover, the success of this technology option requires also an accelerated roll-out of the charging infrastructure. Both the transmission and the distribution network in the European Union require to be upgraded to ensure complete coverage of all transport networks. Original technologies such as catenary lines and pantograph systems can also deliver electricity to large and small vehicles (rail, tram, metro, trucks, cars). However, regarding the impacts on the distribution system, the aspects of interest rely on the deployment of electric vehicles and plug-in hybrid electric vehicles; hence, only light-duty vehicles that can be plugged into the distribution grid.

Besides electrification, digitalisation represents an overarching trend in the EU; in fact, pursuing **digitalisation allows monitoring and controlling the energy processes by enabling the management of the decentralised energy system**. All the future decarbonised scenarios rely on the benefits brought by the adoption of digitalisation in the different sectors. Therefore, to sustain the consumption's electrification and the high share of distributed renewable generation, the distribution system requires achieving a high level of digitalisation to enhance the observability and controllability of the network infrastructure.

Furthermore, the electric power generation with renewables and the electrification of the final energy demand require the **better integration of the different sectors and the related infrastructures**. Sector integration allows maximising the exploitation of the available resources contributing to the decarbonisation of the energy system. Additional research, innovation and demonstration are required to understand the crisscrossed impacts among the different sectors and infrastructures. To illustrate, the electrification of the car stock means coupling transportation with the electricity sector, hence, coupling the people's mobility attitude with the electricity behaviour. Therefore, the electrification of the car stock requires to be studied from a joint electric-transport perspective. Moreover, the joint analysis allows to avoid stranded assets, unnecessary overdesign, and provides comprehensive information for investments decisions.

Regarding specifically the building sector, all scenarios consider that the number of dwellings and their average size will gradually increase [2]. Considering the future decarbonised scenarios, one of the contact points between the building sector and the distribution system is represented by the requirements for smart meters in households and buildings. **The adoption of smart meters and the investment in advanced metering infrastructure (AMI) are necessary conditions to enhance the observability of the network infrastructure** to face the decarbonised scenarios. Moreover, smart meters' adoption also produces positive externalities such as increased consumers awareness and the consequent energy savings. Furthermore, the adoption of smart meters jointly with smart technologies empowered by ICT advancements enable new services and new business opportunities related to the participants in the energy markets (i.e. aggregators that aggregate households for providing system services to the grid allowing to household to achieve energy bill savings. The availability of enhanced information on the electric energy exchange allows tuning up the aggregation activities. Bid data management and household forecast services may also represent relevant business opportunities enabled in the future distribution system).

Also, digitalisation represents the core technology for smart buildings. The adoption of building automation technologies may require investments which breakeven point stays in the long run. However, building automation leads to energy efficiency, optimisation of local electricity consumption and generation, and reduction of CO_2 emissions. Moreover, **smart buildings are a source of flexibility for the distribution system** since they could effectively adapt their operation to the occupants' needs while pursuing optimal energy performances and interacting with energy grids operation. Smart technologies contribute optimising the technical building systems' operation (e.g. heating and air-conditioning systems), maximising the use of renewable energy sources, and participating in demand-side response programs. Smart technologies can potentially lead to significant reductions in the space energy demand of heating & cooling. Smart buildings can dynamically interact with the energy system, providing energy flexibility to the grid by managing demand and optimizing self-consumption. When available, on-site storage capacities (both stationary and embedded in appliances and vehicles) can be integrated into the building management system and can provide flexibility to the energy networks. Where smart charging capabilities are available, the diffusion of smart buildings contributes to the uptake of electric (battery or plug-in hybrid) vehicles. Active buildings, thus, represent a manageable part of the energy system that contribute to enhanced flexibility. Nearly zero-energy buildings also have to be considered in assessing the impacts of smart buildings on the distribution networks. The energy exchange of the nearly zero-energy buildings represents a net load with a novel behaviour for the distribution system which has to be adequately considered in the planning and operation stages.

Table 5-1 resumes the main challenges and recommendations for the distribution system to address future long-term scenarios.

Table 5-1. Main challenges and recommendations for the distribution system concerning addressing the future long-term scenarios

The main findings, challenges, and recommendations for the distribution system concerning addressing the future long-term scenarios are:

- address the uncertainties related to the future scenarios also regarding local information (e.g., load and generation type and capacity in the area of interest, technology option deployment, the status of the network);
- recognise that "one solution does not fit all", the local conditions are fundamental for designing the optimal strategy to achieve the overall energy and climate goals;
- recognise that the future distribution system will be tremendously transformed compared to the current situation, irrespective of the specific high-level scenario.
- unlock the potential of distributed energy storage, demand-side response programs, and electrification of the mobility;
- address sector coupling achieving the optimal integration of different sectors and related infrastructures;
- promote digitalisation to allow monitoring and controlling the energy processes by enabling the decentralised management of the distribution system:
    - by adopting smart meters and investing in advanced metering infrastructure (AMI) as a necessary condition to enhance the observability of the network infrastructure;
    - digitalisation and integration of smart buildings in the distribution system operation.

5.2 Discussion on the challenges of operation and planning of future distribution networks

Operating and planning the future distribution system is subject to high uncertainties, mostly due to the various possible scenarios up to 2050 and the various operational schemas that could be adopted in the long term. As shown in section 4, out of the set of technology options, different long-term scenarios up to 2050 contain various prominence of different technology options. The extremer scenario paths are characterised by the expected technological evolution and maturity of given technology options, such as battery technology or fuel cells.

The high-level analysis presented in chapter 4 shows the principal requirements for flexibility, depending on the deployment and design of technology options in various long-term scenarios. A quantitative analysis of the flexibility needs that sufficiently considers the local conditions is essential for distribution network planning. Likewise, regulators need quantitative analysis to shape efficient regulations, enabling the cost-effective development of the sustainable energy system.

Various tools to support the quantitative assessment already exist, and other tools or models are emerging. EUniversal D1.2 presented a characterisation of distribution network control and management tools and technologies to enable the participation of DER in flexibility markets [106]. This characterisation is used as a reference frame in this section while projecting potential DSO needs for operation and planning tools up to 2050.

The principal approach to select or develop models to plan future distribution networks, which includes non-conventional expansion based on flexibility, is illustrated in Figure 5-1. Non-conventional grid expansion, also referred to as non-wire alternatives, includes all expansion technologies besides conventional transformer and conductor expansion. Some examples are the secured adoption of load, generation and storage through the use of flexibility or curtailment, regulating distribution transformers, dynamic line rating, advanced voltage control and dynamic network configuration. Following the general procedure described in this section, the operation and planning of future networks are treated consecutively in the following paragraphs. Finally, recommendations on model or tool selection for long-term planning are provided in section 5.2.4. The main findings, challenges, and recommendations related to the future distribution system operation and planning are resumed in Table 5-3.

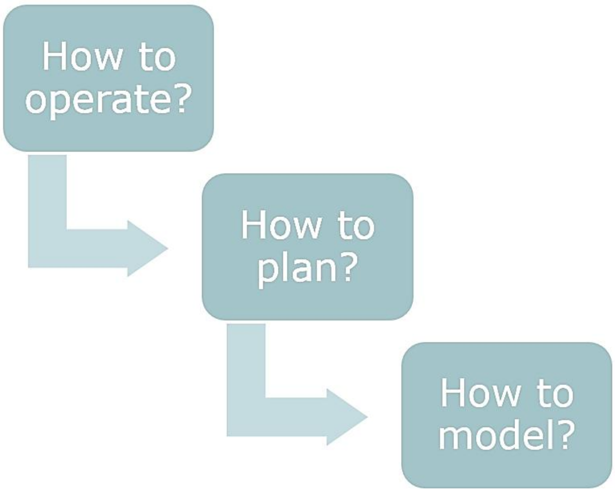


Figure 5-1. Illustration of the approach for quantitatively assessing the flexibility needs in the distribution system

5.2.1 *Long-term DSO operation needs, up and beyond 2030*

To manage flexibility reliably and cost-effectively within the future operational procedures of the DSO, the distribution system is shifting to an actively managed network [4], [9]. This paradigm shift brings the need for increased system observability and system controllability as the foundational elements of active distribution network operation. A further key element for active distribution system management within large interconnected systems, such as the synchronous grid of continental Europe, is the increased need for communication and coordination with existing and new system actors.

Validation with simulation tools is usually addressed before testing or implementing new operation procedures to the distribution grid. Such tools can commonly be found, both in the commercial sector as well as within the scientific community. To select or design the simulation tool for the required validation, the **operational procedures satisfying future DSO needs must be identified**.

Particularly relevant for distribution system operation are **new operational schemes for satisfying existing and emerging DSO needs involving traditional practices and flexibility provision**. In D1.2, a set of grid and non-grid DSO needs and the respective services have been identified, as reported in Table 5-2 [106].

Table 5-2. Grid DSO needs and respective services
Source: [106]

Need type	Needs	Service	
Grid DSO needs	Voltage control	Reactive power management	Steady-state control
			Dynamic control
		Active power management	
	Congestion management (CM)	Operational	
		Short-term planning (D-1 to M-1)	
		Long-term planning (>M-1 to Y-1 or more)	
	Service restoration	Black Start for distribution island	
		Isolated/Islanding operation mode	
	Voltage sag mitigation	FRT	
Non-grid DSO needs	Planning and predictive management	Flexibility forecasting	
		Generation forecasting	
		Load forecasting	
	Observability of the flexibility Procurement mechanism (and settlement) Improved coordination between SO	Visibility over available flexibility	

Beyond 2030, it can be expected that the services satisfying the presented needs are well integrated into the operational DSO procedures. However, depending on the evolving scenario, some new DSO needs could emerge others intensify in their relevance.

Inertial response

One example is the inertial response, which up to 2030 has been identified as a TSO need in D1.2 [106]. In low inertia power systems dominated by power electronics instead of rotating electric machines, needs for inertial response can emerge, even on the distribution system level. Black-start capability and island operation mode would require a physical behaviour and technical implementation in the same scope as inertial reserve might be a flexibility support. Therefore, technical implementation and standardisation should take the potential long-term need for inertial reserve provision within the distribution system into account.

Digitalization of distribution systems

As Information and Communication Technology (ICT) is increasingly applied on all voltage levels of the power systems, supporting ever more complex automation and coordination tasks, the design process of such systems gets more multifactorial. Following the perspective of Systems Engineering, electric power systems are evolving from a massively interconnected, complicated system to a complex system [107]. Therefore, the modern power system is defined as complex cyber-physical power systems (CPPS) [108], [109]. Due to this evolution, the observability of the network state in the distribution level can increase significantly, providing the basis for active network management. Placing sensory equipment to measure the grid state strategically in the distribution network levels, enables a great observability leap for relatively low cost, if combined with state estimation algorithms.

The digitalisation of grid monitoring and control and local market functionality can bring a higher degree of flexibility [110]. This approach, to achieve a scalable ICT structure for Renewable Energy Communities (REC), Citizen Energy Communities (CEC) or more general microgrids, is currently based on common computer science technology in combination with Open Platform Communications Unified Architecture (OPC UA) as the state-of-the-art industrial automation middleware that supports interoperability in smart energy systems [109], [111], [112].

5.2.2 *Long-term planning: DSO planning needs, up and beyond 2030*

Long term planning with a time horizon up to 2050 needs to consider the input data based on the respective scenario paths and the feasible operational models related to these. The long-term risks of the scenario paths are significant, and therefore, planning with time horizon 2050 needs to identify potentially emerging path-dependencies and lock-in effects early on. This will allow applying countermeasures and reducing potential overinvestments resulting from high switching costs based on technology lock-in on the time-scale of the planning horizon 2050.

Structural aspects of energy system scenarios

Energy system models often lack sufficient modelling of the distribution system, therefore providing high uncertainties regarding the cost of DG integration at the distribution level. In energy system planning, decentralization is often debated around societal, political and social issues, rather than from the technical perspective. Therefore, it is important to **define decentralization in a technical context and introduce the degree of decentralization as a quantitative measure of decentralization**.

A high degree of decentralization is expressed by a high share of decentralized renewable energy installations (e.g., onshore wind, roof-top PV, geothermal power plants) and a high spatial and temporal correlation between local generation and consumption. A high degree of decentralization can lead to higher energy system costs, mostly due to a higher need for storage and flexibility due to the lack of inter-regional balancing of consumption and generation by power networks [113]. Comparing techno-economic model calculations, the system models with a higher degree of decentralization frequently have a higher cost associated, though often only by a few per cent [114]. On the other hand, decentralized control models can also decrease local grid expansion needs, where the regional distribution of renewable power generation is the main factor for variations in grid expansion needs.

Another factor that influences the energy system scenarios is the scale of European inter-connectivity. The degree of European interconnectivity can be defined as a function of the number and capacity of interconnectors (i.e., inter-area) that connect the Member States and sometimes bidding zones. A high degree of European interconnectivity allows for stronger integration of markets and a system-wide cost-effective technology mix. The latter is mainly due to the lower need for (long-term) storage, such as hydrogen caverns and gas turbines, though on a geographically wider scale. Besides the number and capacity of interconnectors, the amount of energy exchanged is an important factor for energy system scenarios to consider for total system welfare as well as geopolitical considerations. Such considerations impact long-term distribution planning indirectly with potentially high impact.

Long and medium-term load and generation forecasting

The knowledge of the electricity demand shape is essential for most applications and studies on the power system regarding network operation and planning [115]. In general, to estimate the total load demand or production in a given instant or forecast them in a specific time horizon is not sufficient for network studies. The availability of time series is necessary to represent the impact of demand coincidence and generation adequately–(load homotheticity), which causes voltage issues and network congestions, especially at the medium-voltage (MV) and low voltage (LV) levels where DERs are connected [115]. Therefore, **the accuracy of load and generation forecasting is essential for power systems operation and long-term planning; the reliable modelling of the energy demand of single customers is crucial for accurately assessing the flexibility potentially available**. While the forecast quality is already relatively high on an aggregated level, forecasting for disaggregated DER, for example, in the LV network of the distribution system, is very challenging. For grid LV operation and especially for planning, the extreme conditions are the critical situations for which the network configuration and operational plan has to be shaped. As the aggregated DER behaviour on higher voltage levels aligns well with the forecasted load and generation curves, one could argue that on lower voltage levels, the lower level of aggregation of the resources' behaviour makes crucial the forecasting quality to predict critical situations (e.g., peak-load, reverse power flow).

Interoperability

One way to early account for the uncertainty regarding flexibility sources from technology options in long term scenario paths is to **ensure standardisation and interoperability of the flexibility provision**, irrespective of the technology option that provides it. Table 50 of D1.2 maps DSO Services to DER that could support these services [106]. To account for some of the long-term risks, technology options, and amongst them DER, should be designed or adapted to provide services to the DSO in a unified and interoperable way. This reduces path dependency and lock-in effects as the technological evolution progresses and technologies become mature.

Resiliency of active distribution networks and service restoration

Resilience has been and still is a key design criterion for power systems. One can even argue that the societal value of power system resilience is increasing nowadays for two reasons. On the one hand, our societies increasing dependency on information technology and automation makes the reliable availability of the power system even more indispensable. On the other hand, the power system is getting strongly coupled to other critical infrastructures such as gas supply, supply of heating and cooling, and mobility. Furthermore, the expected increased frequency and intensity of extreme wheatear events will lead to more frequent severe stress conditions for the distribution networks. Therefore, resiliency requirements are of utmost relevance in the path towards the future distribution system.

Decentralised systems that can be operated in islanded mode and re-connected with the overall system at a given moment can support emergency operation and service restoration. However, the costs associated with this security gain are not well researched [114]. However, such automatic islanding and resynchronization and **black-start support capabilities of islanded microgrids or distribution systems are grid needs that could potentially become of high importance in the long term**. Long-term planning should account for such service provision needs as conventional black-start procedures become increasingly uncertain due to the lower share of capable conventional power plants at the transmission grid. Realistic large-scale networks that can consider local emergency supply needs, such as for hospitals, or take other critical infrastructure and emergency processes into account are especially promising.

As conventional risk management approaches, with large repositories of identified risks, are not feasible in complex CPPS, a transition to a resilience management approach is suggested [108]. If the proposed resilience management approach is applied, implications on the grid expansion planning process follow for the planning, procurement, installation and operation stages.

A given grid expansion technology option might increase overall resilience management capability as it improves adaptability (e.g. local voltage control or distribution grid automation systems). However, the contribution to the resiliency management capability given by different expansion alternatives, including conventional grid expansion, has to be considered in the planning stage. The complexity of the evaluation calls for developing new methodologies and tools for distribution system planning.

5.2.3 *Modelling the distribution system: realistic large-scale simulation and planning models*

Conventionally, mostly representative feeder networks have been used to validate results in distribution operation and planning studies. Though real networks data, if available, or realistic synthetic networks data, promise a much more concise validation process as well as additional insights beyond the planning process. Due to the lack of available network data for the research community or network regulators, sufficiently accurate synthetic Reference Network Models (RNM) with realistic statistical representation are generated and used [116], [117]. Synthetically created RNMs are called greenfield RNM, while RNM are generated as an alteration of an initial realistic large-scale synthetic network are called brownfield RNM.

There is an increasing need for RNM and other network simulation models to integrate other energy systems such as gas as well as heating and cooling networks. Moreover, due to the increasing interest in sector coupling, as described in sections 2.1 and 3.1, the different infrastructures of the different sectors need to be modelled jointly. Beyond 2030, ubiquitous computing in combination with AI or IoT, in general, could also significantly impact distribution system operation.

Related to grid simulations, EUniversal Task 10.1 performed interviews with 11 DSOs on distribution network planning. Findings show that most DSOs are working towards handling comprehensive network data and the simulation of their networks using algorithms for power flow calculation and optimal power flow calculation instead of resorting to empirical rules or simplified network representation and parameter sensitivity monitoring. This trend will **lead DSOs to have a digital twin of the physical network and then to be able to simulate with high accuracy the network behaviour**.

5.2.4 *Recommendations for long-term planning and operation*

Long-term planning scenarios need to consider the **decentralisation** of the power system also regarding monitoring and control practices. The decentralisation of these practices will lead to CAPEX and OPEX for the ICT infrastructure needed to coordinate a highly decentralised system with very high security of supply requirements.

Forecasting load, generation and flexibility becomes essential for distribution system operation and consequently for planning. Therefore, continuous forecast and availability assessment of resources is needed for cost-effective and resilient operation and planning in the future distribution system.

Resilient active distribution network operation includes service restoration capabilities that potentially allow automatic distribution system islanding, re-synchronisation, and black-start support. Such dynamic capabilities are increasingly becoming relevant due to the likely higher interconnectivity and complexity of actively managed distribution systems as well as the higher likelihood to operate close to stability limits.

Consequently, this large amount of ICT in potentially emerging ubiquitous computing and coupling with the IoT domain increases the attack surface in cyberspace and makes **cybersecurity** essential.

Realistic large-scale distribution system models, so-called RNMs, should be used to validate complex active network operation and planning. For DSOs themselves, the use of **digital twin** technology for distribution network simulation also seems increasingly promising.

Table 5-3 resumes the main challenges and recommendations concerning the operation and planning of the future distribution system.

Table 5-3. Main challenges and recommendations concerning the operation and planning of the future distribution system

The main challenges and recommendations concerning the operation and planning of the future distribution system are:

- define operational procedures to satisfy the future DSO needs, define new operational schemes that involve traditional practices and flexibility services (flexibility or curtailment, regulated distribution transformers, dynamic line rating, advanced voltage control and dynamic network configuration);
- improve the energy models: define decentralization in technical terms and introduce the degree of decentralization as a quantitative measure, model the impact on the distribution system of interconnections among different energy systems;
- enhance load and generation profiling: increase the temporal accuracy and spatial granularity of load and generation forecast.
- ensure standardisation and interoperability of the flexibility provision;
- enhance the distribution system resiliency to enhance system restoration capabilities that potentially allow automatic distribution system islanding, re-synchronisation, and black-start support;
- obtain detailed representations of distribution networks to achieve digital twins of the physical grid to enable high accuracy simulations and advanced asset management.

5.3 Discussion on the flexibility procurement mechanisms

As observed in section 4, all scenarios for the future distribution system concern developing technology options able to provide system services to the DSO. Any mechanism for acquiring system services shall aim for technology neutrality, as discussed in EUniversal Deliverable 5.1 [103]. Therefore, it is relevant to have in mind the principal characteristics of flexible resources. Due to the great variety of resources that can support the power system by providing system services with their flexibility, this section provides a brief and general description of the flexible resource characteristics. Deliverable D3.1 "Flexibility Toolbox" describes the different technologies that could provide flexibility in the distribution and transmission system, such as different storage technologies and demand-side flexibility [118]. DSOs can use a wide range of mechanisms to acquire flexibility from resources owned by other players of the distribution systems (e.g., distributed generators, prosumers, customers, aggregators). The key mechanisms of interest of EUniversal have been identified in EUniversal Deliverable 5.1 [103] and are summarized in Table 5-4. Not all possible mechanisms for acquiring grid services have the same effectiveness if exploited in different grid contexts. Therefore, **the context of the need for system service has to be examined to identify the relevant attributes and optimally design the flexibility procurement mechanism** [103].

Through the mechanisms in Table 5-4, the DSOs can acquire system services from Flexibility Service Providers (FSP). Market-based or regulated compensations for the flexibility provided are considered in all mechanisms, except in the obligations-based ones, in which the DSO can use the flexibility of resources without any compensation. However, this option would be the least preferred as it does not provide incentives to minimise the overall system costs and the technology evolution towards more flexible resources. Bilateral contracts should be relegated to specific cases in which only one or few potential providers are technically able to solve a particular DSO need.

Local flexibility markets could be complex to implement and operate, and the complexity of the market procedure may represent a barrier to the participation of small FSPs. However, flexibility markets should be preferred, unless the context makes them impossible due to liquidity or complexity issues. Therefore, local characteristics have to be carefully assessed to ensure enough liquidity and prevent market distortions before developing a local flexibility market. Local flexibility market is generally a technological neutral solution to incentivise assets of different nature to compete to provide grid services. Tailor-made solutions that can be adapted to the DSO needs and FSPs characteristics. However, the implementation of these markets has many design elements and challenges to be considered. Local flexibility markets may require complex coordination with existing markets and different agents (e.g., TSO-DSOs, DSO-DSO, DSO-Aggregators). Different coordination schemes are possible and they should be carefully chosen to keep a balance among different criteria (e.g. gains on economic efficiency vs implementation costs). It is relevant to define the roles, functions, and responsibilities of the different agents.

Dynamic network tariffs and connection agreements could incentivize small business and residential customers to provide implicit flexibility since the lower complexity perceived by the final electricity users, compared to the other alternatives. Efficient dynamic network tariffs should provide short-term and long-term marginal costs signals and recover the rest of the network costs through residual fixed network charges. By applying such tariffs, efficient economic signals are provided to customers to reduce short-term and long-term network costs incentivizing the development and efficient operation of new technologies such as distributed generation, demand flexibility, storage, electric vehicles, etc. A mild approach could be to include some sort of time-of-use charges. These are simpler to implement and provide more predictability for consumers. The trade-off is that they are less accurate as they take real-time grid conditions less into account. Furthermore, price differentiation can be applied at voltage levels within a zone or at national level.

Residual network costs should be allocated in a non-distortive manner to avoid interfering with efficient price signals but to ensure cost recovery and economic sustainability of the electricity system [103], [119]. Equity criterion should be considered to design the associated costs. There is no first best option to allocate such costs, fixed charges based on income levels, contracted capacity at peak and mid-peak hours or past energy consumption are options that fulfil the non-distortion and equity criteria but have other implementation challenges.

The flexibility procurement mechanism has to be **reliable**, considering the local context, the adopted mechanism has to be **able to procure a sufficient amount of service for guaranteeing a secure operation of the power system**. In particular, it represents the certainty that the contracted FSPs deliver the contracted service. Therefore, tailored customer engagement strategies are required.

It is relevant to mention that the implementation of each mechanism (both regulated and market-based) has costs that may vary depending on each specific realisation feature. For example, bilateral contracts can contribute to price discovery (i.e. reducing information asymmetries) but require negotiations between the DSO and FSP. Cost-based remuneration, once set, has low implementation costs but, on the contrary, may entail higher costs related to the computation of the regulated prices. Different functions have to be implemented for markets (e.g., market platforms with clearing and settlement) so that implementation costs could be not negligible.

EUniversal Deliverable 5.1 [103] provides a detailed description of mechanisms for acquiring system services and discusses peculiarities, pros, and cons. This discussion also focuses on implementing one mechanism over another considering the local characteristics and the compliance with the policy criteria is available.

Table 5-4. Mechanisms for flexibility procurement Part 1/2. Source: [103]

Mechanism	Definition
Flexible access and connection agreements	Flexible access and connection agreements are agreements between the system operator and the FSPs in which the latter agrees to have the temporal changes in the available connection capacity. Demand could be temporarily reduced during the periods of load peak demand, whereas generation could be curtailed to avoid network issues such as congestions or voltage issues. This mechanism applies exclusively to new connections. Flexible access and connection agreements is an implicit[8] procurement mechanism.
Dynamic network tariffs	Dynamic tariffs concern devising time (and locational) differentiated network tariffs, which can be adjusted to reflect the necessary temporal and spatial cost variations. The grid users are incentivised to change their consumption and/or production according to the grid operation and future network needs. Dynamic network tariffs is an implicit[8] procurement mechanism.
Local flexibility market	Local flexibility markets include long-term and short-term pools in which offers are received from FSPs. A long-term mechanism could be used in planning activities to procure flexibility by contracting long in advance the potential service providers. The local market extension depends on the grid characteristics, i.e. the market area can encompass only a portion of the distribution network. The size of the local market is site-specific. The DSO will utilise flexibility based on its willingness to pay for it and the available solutions and the type of flexibility product required. A local flexibility market seeks to promote competition among flexibility providers. Local flexibility market is an explicit[9] procurement mechanism.
Bilateral contract	A bilateral contract is a binding agreement between two parties. In the context of system services, one side is represented by the system operator while the other is the FSP. A bilateral contract requires a negotiation process between the two parties. Unlike the flexible connection mechanism, the bilateral contract mechanism is in general exploited for existing connected resources and constrained situations. Bilateral contract is an explicit[9] procurement mechanism.

[8] Implicit (or price-based) mechanisms refer to the prosumers' reaction to price signals. As implicit mechanisms reflect the variability on the market and the network, prosumers can adapt their behaviour (through automation or personal choices) to save on energy expenses by shifting their load and/or generation to periods with low/high energy prices, or low grid prices [120], [121].

[9] Explicit (or incentive-driven) mechanisms involve the provision of committed, dispatchable, flexibility that can be traded on the different energy markets (wholesale, balancing, congestion management, etc.). Because this type of flexibility is dispatchable, and can be tailored to the markets' exact needs (size and timing), it may offer specific added value for e.g. balancing and capacity management [122], [123], where the system flexibility requirements are determined in advance [120], [121].

Table 5-4. Mechanisms for flexibility procurement Part 2/2. Source: [103]

Mechanism	Definition
Cost-based mechanism	A cost-based mechanism deals with the remuneration of the flexibility provided by the FSP based on the actual costs of providing the service. To illustrate, the cost-based mechanism for flexibility can determine the price of the service provided according to the opportunity cost of active power generation curtailment. The cost-based mechanism requires an acknowledged audit process of the provider's costs and financial margin that allows providers a return. Cost based is an implicit[8] procurement mechanism.
Obligation	The obligation mechanism for flexibility provision defines the mandatory service provision from the FSPs. The service requested by the system operator to the FSPs is not remunerated, but instead, the FSPs are obliged to contribute with their flexibility.

Table 5-5 resumes the main challenges and recommendations concerning the mechanism for procuring flexibility in the future distribution system.

Table 5-5. Main challenges and recommendations concerning the mechanism for procuring flexibility in the future distribution system

The main challenges and recommendations concerning the development and adoption of the mechanisms for procuring flexibility in the future distribution system are:

- Identification of the mechanism for procuring flexibility from connected resources that best suits the distribution system needs context (discussed in Deliverable 5.1) [103].
- Fair distribution of the network tariffs among the users, new equilibrium between volume-based and capacity-based tariffs (discussed in Deliverable 5.1) [103], [119].
- Develop mechanisms that engage enough customers to achieve adequate flexible capabilities.

5.4 Discussion on regulation for the future distribution system

As described in sections 2, 3, and 4, the growing connection of renewable generation to the distribution system may produce significant network congestion and voltage problems [124]. Moreover, the possible growth of demand and the presence of new loads make grid planning more challenging and uncertain [125]. Therefore, DSOs should quickly adopt innovative grid planning and operation to address these challenges efficiently, using flexibility mechanisms [4], [126]. Resorting to flexibility mechanisms that involve distributed generation, controllable demand, or storage may support grid planning reducing investment needs and DER connection times [125].

Starting from the late 1980s, in Europe, the electricity market restructuring based on the liberalization, unbundling, and liberalization concepts pushed the fragmentation of the electricity sectors of the Member States [127]. However, the grid ownership and the system operation have been considered to have natural monopoly characteristics [128]; therefore, regulated operators have been instituted for the transmission (TSO) and distribution (DSO) systems. The role of each regulated operator is to own and operate the power system to guarantee a reliable electricity supply and universal network access to third parties [129]–[131]. The TSOs and DSOs have to guarantee universal access to all third parties (generators, loads, storage facilities) at any point of the network [130], [132]. The traditional control practices are mined by the reduced availability of large power plants, the presence of Distributed Energy Resources (DERs) since the emergence of bidirectional power, and the emergence of new loads [9], [133], [134]. Even if the connection of third-party resources may be seen as a part of the problem since the introduced issues, these assets can contribute to an efficient power system evolution if adequately managed.

New control practices and new service providers are needed to ensure the support required; the decentralization of operation and market processes encourages the exploitation of smaller generation facilities and loads to solve local grid problems [135]. In this context, **regulation needs to experiment with innovative frameworks** to address the changes driven by the energy transition and **allow the design of profitable business models** for the relevant actors by **enhancing societal welfare and preserving consumer protection**. The active participation of third-party resources, which can be connected to either the TSO or the DSO level, may relieve contingencies, increase the hosting capacity, and provide an effective way for improving the coordination between TSOs and DSOs [9], [136], [137]. In a liberalised electricity sector, new service provision capability investments have to be encouraged, fostering competition among service providers [138]. The energy transition requires the evolution of the mechanism for procuring system services; in this context, **it is fundamental to provide indirect economic stimulus to encourage third-party investments in the most effective technologies and nodes** [138].

Furthermore, **regulation has to study the new roles and responsibilities that can be assigned to the DSO** to unlock the distribution system potential. The implementation of market-based flexibility procurement requires, on one side the flexibility providers as sellers and on the other side the DSOs as buyers. The current regulation considers DSOs as regulated neutral parties. Nevertheless, in the market-based flexibility procurement, DSO may also play the role of the market operator. Therefore, on the one hand, regulation needs to establish dedicated procedures to enable flexibility providers to offer generation capacity or controllable demand, and, on the other hand, to allow and incentivize the DSOs to procure and use these flexibility for system services in a cost-effective way.

Regulation has to design **regulatory frameworks to enable local procurement of system services in which grid expansion competes with flexible resources on a level playing field**. Implementing flexibility mechanisms calls for innovative network planning and operation practices that require novel organizational models and determine new cost structures for the DSOs [125]. However, since the novelty of the topic and the uncertainty related to the future flexibility needs, National Regulatory Authorities (NRAs) require tools to assess how these innovations will evolve and impact power systems, the electricity market, and society. Moreover, DSOs have to be supported by defining effective technical and economic strategies to address future scenarios. Deliverable D10.1 of the EUniversal project examines the current practice and future target model of distribution network planning, focusing on the trade-off between flexibility and traditional network investments.

The Clean Energy Package, in Directive 2019/944, established that DSOs should be incentivized to procure flexibility for system services instead of resorting to traditional grid expansion if more economically efficient [139]. Moreover, flexibility should be procured whenever possible using market-based mechanisms and standard products. Therefore, DSOs and NRAs should unlock the use of flexibility in the short term [125]. The DSOs network development plans shall include demand response, energy efficiency, energy storage, or other resources as an alternative to system expansion [139].

The key points of interest for regulation innovation to fully enable the future role of the DSO are [140]:

- the promotion of the implementation of smart metering and smart grid infrastructures,
- the definition of clear price signals to guide the end-user behaviour,
- the definition of a regulation that incentivizes the active distribution system management,
- the definition of a clear regulation for data collection, management, sharing rules, and consumer privacy,
- the definition of clear rules for the TSO-DSO coordination,
- the definition of the framework that defines the procurement of system services from third parties.

Regulation has to consider the new activities, responsibilities, charges, and opportunities that characterise the DSO role in the future distribution system. Therefore, an updated regulatory framework for remuneration of CAPEX and OPEX that consider the exploitation of flexibility from third party owned resources is also required [140], [141].

Addressing the challenges related to the future decarbonised scenario requires testing new services and products that are not yet stipulated or permitted under the existing regulation. Procuring system service from resources connected to the distribution system that third parties own is a novelty for the power system. Therefore, designing and implementing local flexibility mechanisms for DSOs is pioneering and requires regulatory experimentation to explore all possibilities, local conditions, and assess strengths and weaknesses. It is expected that the use of regulatory experimentation may help the NRA and DSOs to obtain evidence that helps the elaboration of the regulations needed for the implementation of the future flexibility mechanisms.

In general, regulatory experimentation is based on pilot projects, regulatory projects, and regulatory sandboxes. Pilot projects are the most common form of experimentation of DSOs in Europe, according to the latest report of the Joint Research Centre (JRC) - the European Commission's science and knowledge service [142]. Regulatory projects, in general at the country level, promote initiatives for the deployment of specific technologies. Similarly to pilot projects, the regulatory sandbox occurs in specific areas (e.g. a specific network area of the distribution system). The regulatory sandboxes are established under the cooperation of the market operator, the regulator, and the DSO. Recently, several countries created "safe spaces" or "sandboxes" (i.e. an "area" within a system or market in which a different regulation applies for a certain period) [125].

Regulatory sandboxes are instruments of legislation to experiment with innovative business models or technologies, which, under normal conditions, would be hindered by legal or regulatory barriers [143]. They provide an experimental environment to foster innovation and business model development. This can be achieved by granting stable conditions for a limited time (and often limited geography) by opening, repealing, or disabling rules and regulations or by keeping existing regulation and compensating the participants. In this way, new products can be developed in a real-world environment without applying some of the usual rules and regulations. As shown in Table 5-6, regulatory sandboxes have been introduced to promote entrepreneurship and innovation within several economic segments while keeping consumer protection and regulatory oversight [125]. Successful results have been achieved concerning the promotion of innovation [144]. However, concerns related to the adoption of sandboxes could be related to the riskier decisions taken by the companies and the allocation of economic privileges to specific firms [145]. Regulatory sandboxes will also be studied in detail in deliverable D10.2 of the EUniversal project.

Regulatory experimentation and the adoption of regulatory sandboxes are seen as useful means to address the relevant issue of distribution networks in a decarbonised scenario. The main challenges to be addressed regard market integration, distribution network planning, flexibility remuneration, and TSO-DSO coordination.

The Clean Energy Package encourages the integration of flexibility markets for DSOs in the current European electricity market architecture. The development of a new European Network Code on flexibility is currently under discussion.

Specific regulations for distribution network planning and operation still have to be defined for effectively unlocking the flexibility from third-party resources.

The current TSO-DSO coordination scheme needs to evolve to include other market players (e.g. aggregators). Moreover, real-time information exchange is required to coordinate TSO-DSO flexibility acquisitions by maximising the economic efficiency and avoiding conflicts in FSPs activations [146].

Table 5-6. Relevant aspects of regulatory sandbox experiences in Europe
Source: [125]

Country	Sandbox legislation	Experiences
United Kingdom	Yes	Peer-to-peer energy marketing, new rate schemes, energy generation and marketing schemes, self-generation
Germany	No, demo projects with flexibility compensation mechanisms are used	Flexibility in distribution (use of renewable generation, storage to relieve congestion and avoid new investments).
Netherlands	Yes	DC transmission networks, flexible rates, regulatory transmission, self-generation and storage changes
Italy	No, but similar approximation "regulatory projects"	Smart Grid, storage, technical management of electricity transport limits, electric vehicle chargers, smart metering, flexibility and demand management
France	Yes	Aimed at specific articles of the energy and climate law, but open to any proposal in that field. Focuses on experimentation in T&D networks, storage and gas and DER uses. Four years, renewable for another period under the same conditions. The regulator (CRE) is in charge of experimentation.

Moreover, to foster the power system transformation, political drivers, such as the Clean Energy for All Europeans package, require TSOs and DSOs to regularly submit a transparent development plan in which innovative assets and services will be used for unlocking the system flexibility to maximise the use of the existing infrastructures [147]. In these development plans, flexibility (e.g. generation management, demand-side management, system reconfiguration) have to compete with traditional network reinforcement (substation and line construction or upgrading). Therefore, reliable approaches for project appraisal able to compare the different measures is of interest [6], [148], [149]. **Decision-making support tools able to handle the wide range of impacts determined by the smart grid initiatives are required**. These tools are able to consider heterogeneous and conflicting criteria in which tangible and intangible impacts can be simultaneously evaluated.

Traditionally, distribution planning relies on economic-based tools (i.e., Cost-Benefit Analysis – CBA) that require converting all project impacts in monetary terms. CBA is an acknowledged tool for considering costs and benefits that can be directly monetised. In contrast, the appraisal of projects showing broad effects and non-negligible intangible impacts shows some underlying shortcomings related to quantifying, monetising, and discounting the impacts [150]–[152]. This is the case of the future distribution systems since the novel features and services will influence customers' daily habits; therefore, the entire society.

In Europe, several guidelines promote multi-criteria assessment frameworks for smart grid projects [153]–[156]. Multi-Criteria Analysis (MCA) is an operation research tool for complex decision making that supports the decision-makers in identifying the best option among a set [157], [158]. MCA allows considering heterogeneous and conflicting criteria: tangible and intangible impact can be simultaneously evaluated. Unlike CBA, MCA does not require monetising all the assessed impacts. Nevertheless, MCA and CBA are not conflicting tools; appraisal approaches that combine MCA and CBA are promoted for the electricity and gas sectors [152], [153], [159], [160] and in the literature [150], [161]–[169]. In the future distribution system, hybrid monetary non-monetary assessment approaches may be of interest to support DSOs and regulatory bodies in the planning processes.

Table 5-7 resumes the main challenges and recommendations concerning regulation of the future distribution system.

Table 5-7. Main challenges and recommendations concerning regulation of future distribution system

The main challenges and recommendations concerning regulation of the future distribution system are listed in the following. • Regulation needs to experiment with innovative frameworks to address the changes driven by the energy transition and allow the design of profitable business models for the relevant actors by enhancing societal welfare and preserving consumer protection. • Regulation has to design frameworks that encourage third-party investments in the most effective technologies and nodes. • Regulation has to study the new roles and responsibilities that can be assigned to the DSO to unlock the distribution system potential. • Regulation has to design frameworks to enable local procurement of system services in which grid expansion competes with flexible resources on a level playing field. • Regulation has to adopt decision-making support tools able to handle the wide range of impacts determined by the smart grid initiatives. These tools are able to consider heterogeneous and conflicting criteria in which tangible and intangible impacts can be simultaneously evaluated.

5.5 Discussion on business models for DSO, aggregators, and FSPs

Discussion on business models for DSOs

The role played by the DSO is characterised by the corresponding responsibilities for ensuring the security and quality of the electricity supply and the requirement to guarantee universal access to the grid to the other actors of the electricity sector. The generation of electrical energy, the retail supply, and ancillary services provision (frequency, non-frequency, and congestion management) are typically considered liberalised activities; while, grid ownership and system operation are considered natural monopolies [128]. Therefore, DSOs are typically regulated bodies that operate the power system to guarantee a reliable electricity supply and universal network access [129]–[131]. In the decarbonized scenarios, different business models can be considered for the liberalized distribution system operation.

Under the current regulation, the distribution system operation is assigned to a unique entity; each DSO is the only entity responsible for the distribution system in a specific area. **Considering the DSO peculiarities, its business model is strongly influenced by the assigned responsibilities and the boundaries for its role concerning electricity supply security, reliability, and quality.** To illustrate, the business models related to a framework in which DSO owns and operates the grid could be different from those related to a framework in which the grid ownership and the grid operation are assigned to different entities (e.g., like in the scenarios in which the TSO owns the transmission grid that is operated by an Independent System Operator – ISO; or the cases in which the CEC owns the local network) [170]. Furthermore, due to the emergence of the local markets for the local procurement of flexibility, the role of the market operation could be covered by the DSO; however, this role could also be covered by an independent market operator [120], [171]–[173]. Additionally, the local energy manager's role could also be covered by the DSO if local energy communities are adopted [173]–[175].

Figure 5-2 depicts the evolution of the power system structure schematically. The blue circles represent the main actors of the power system, the label in yellow represent the categories that belong to the actor “final user”; the arrows represent the active power flows. As illustrated in Figure 5-2, the future power system structure from the DSO perspective will be different from the traditional one. Due to the emergence of distributed generation and storage systems, the electricity flows in the distribution grids became bidirectional; hence, the DSO will play an active central role in the future electricity system operation and planning.

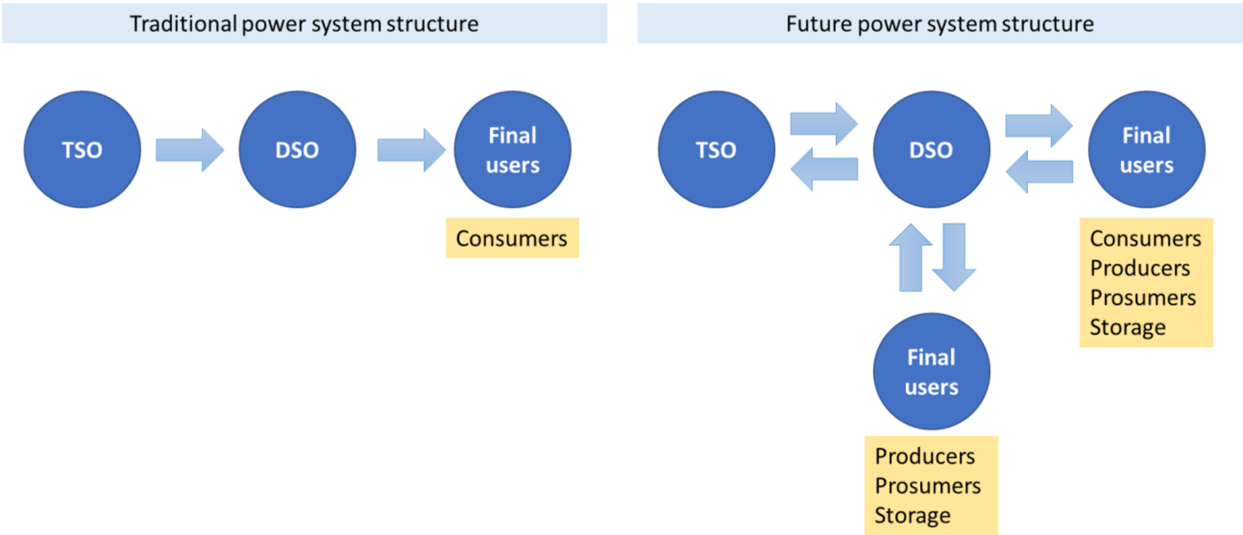


Figure 5-2. Illustrative schema of the ongoing evolution of the power system structure Adapted from: [140]

The conventional role of the DSO is characterized by [140]:

- The universal network access to be guaranteed the distributed resources,
- Planning, maintenance, and management of networks,
- The management of supply outages;
- Energy billing (only if vertically integrated);

The additional activities of the DSO emerging due to the energy transition and that will be crucial in the future distribution grid are [140]:

- Peak load management;
- Network congestion management;
- Reactive power support provision to TSOs;
- Voltage support procurement;
- Technical validation of the power market.

Therefore, several values propositions can characterize the role of the DSO in future decarbonized scenarios. Indeed, DSO would have to ensure the power supply security and quality and universal network access, but could also have to procure flexibility from FSPs. The exploitation of local FSPs requires the DSO to operate the local active distribution system addressing peak shaving, dispatching single or aggregated resources to avoid congestion and voltage problems, procure power generation capacity, and coordinate with the TSO for ensuring the expected behaviour of the TSO/DSO interfaces [4], [9]. Moreover, dedicated TSO-DSO coordination is required when the TSO directly accesses the DER to avoid any constraint violation in the DSO grid [120].

The key resources of the future DSO business model are [140]:

- the enhanced observability and controllability of the distribution network;
- upgrade the network assets to handle reverse power flows adequately;
- the availability of active network devices (e.g., OLTC transformers, static var compensators);
- the availability of advanced data acquisition and communication infrastructures and protocols;

- the availability of software for enhancing the distribution network management.

The DSO business model has to include **clear communication** with the network customers (e.g., aggregators, FSPs), since a solid relationship based on trust, quality, and commitment between the two entities would represent a crucial added value. For example, developing effective DSO-FSP coordination allows FSPs to optimally schedule their activities, considering the network flexibility needs optimally.

Discussion on business models for aggregators

Depending on the adopted procurement mechanism in flexibility markets involving the resources connected to the distribution system [176], [177]. The aggregator is an emerging actor in energy systems; the aggregator is an agent who offers services to aggregate energy production and consumption from different sources (generators, loads, storage) and acts toward the grid as one entity [178]. The aggregator role can also assume the role of facilitator for the participation in the demand side response programs [178]. Although the role of the aggregator is distinct from the grid operator and retailer role, it can be addressed by the same entity that acts as a retailer or a distribution system operator [179]. The definition of business models for aggregator is investigated in literature [170], [173], [176], [180]–[182]. The key resources that characterise the aggregator business model include [177], [182]:

- Energy storage systems;
- Dispatchable loads (e.g., heat pumps, electric vehicles);
- Wind power plants;
- PV power plants;
- Hydropower plants;
- CHP;
- Biogas plants;
- Utility grids.

The aggregator manages the aggregated resources pursuing essentially three key activities that differ both from the technical and the business perspective [182]:

- Demand response: industrial and residential loads;
- Distributed generation portfolio management (e.g., Wind, PV, Biogas, Hydro, CHP)
- Storage systems management.

The **aggregators use an IT system to control the distributed resources and optimise their operation remotely**. The aggregators can provide several system services to the TSO and the DSO [177], [182]:

- Load shifting. Aggregators can enable load shifting to provide demand-side management service to TSOs and DSOs.
- Balancing services. Aggregators can provide a range of frequency ancillary services and mitigate the daily load and generation ramp behaviour.
- Local flexibility to DSOs. Aggregators can provide flexibility to the DSOs (congestion management, voltage control, grid losses reduction) and participate in the local market for flexibility, if in place.

Investments in transmission and distribution grid reinforcements could also be minimized thanks to the aggregators providing demand-side management and load shifting [177].

Since aggregators bundle distributed resources to engage as a single entity in power or service procurement and provision, the customer segment of the aggregator is represented by DSOs, TSOs, and owners of the aggregated resources [182]. Moreover, aggregators can potentially participate in the different wholesale electricity markets: intraday, day-ahead and futures markets (monthly, quarterly and yearly futures markets) [182]. In any case, aggregators' business models have to be based on a **reliable estimation of the value of the flexibility provided**. Since the novelty of the topic and the lack of historical data, obtain a reliable estimation represents a challenging task.

However, the actual conditions that would occur depending on the scenario characteristics and regulatory framework will define opportunities and boundaries for aggregators' business. Therefore, the scenario characteristics will influence the features of the business models that will be adopted. Currently, demand response in the industry and tertiary sector is becoming relevant across Europe, whereas in households, it is not yet developed on a large scale [182]. The success of the aggregation of household resources requires automation for controlling the electricity exchange due to appliances, heating and cooling systems, generators [182]. Moreover, the availability of controllable resources depends on the type and the level of development achieved by the different technology options [182]. To illustrate, the flexible capacity available for an aggregator would change between scenarios based on heat pumps and high-temperature heating and cooling networks. For the success of the aggregators' business models, they have to consider as a key partner the DSO, **a transparent relationship with the DSO** would help portfolio management, hence increase the business model profitability.

The existence of the aggregator in the future power distribution system depends on the fulfilment of several technical and regulatory requirements [177]. The deployment of these technical and regulatory requirements will influence the success of their business model.

Technical requirements for the emergence of aggregators are [177]:

- the high observability (e.g. smart metering) and controllability of the distributed resources;
- accurate data for weather and wholesale prices forecast, load projections;
- the availability of software for generation and demand forecast;
- optimization algorithms and portfolio management;
- reliable and fast communication infrastructure and protocols.

The regulatory requirements for the emergence of aggregators are [177]:

- the participation in wholesale energy and ancillary service markets,
- the introduction of regulation to provide system services to the central/local grids,
- the promotion of the implementation of smart metering and smart grid infrastructures,
- the establishment of local markets for system services,
- the definition of data management and sharing rules,
- the definition of standardized methodologies to compute dynamic prices,
- the definition of standardized procedures and products for retail markets,
- the definition of clear roles and responsibility among market parties,
- the elimination of entry barriers and the full liberalization of markets.

In addition to system services, aggregators can provide to DSOs relevant information regarding the distributed resources increasing the common knowledge regarding demand and generation forecasting [177]. On the other hand, DSOs should ensure a level-playing field for all flexibility providers, securely share consumer and grid-related data [177]. Moreover, aggregators may help decrease the marginal cost of power since contingencies allow the use of flexible resources that cost less than the dispatching of additional power plants [177].

This section highlights how the role and business model of aggregators will depend on the technological and regulatory scenario that will occur. Deliverable D2.2 of EUniversal describes the use cases and roles and responsibilities of the different actors for the EUniversal demos. In addition, in EUniversal D10.1, a business model canvas analysis is performed on the different demo projects.

Discussion on business models for FSPs

Regarding FSPs, the actual business model will depend on the flexibility procurement mechanism adopted (e.g. obligation, network tariffs, connection agreements, or market-based procedures) [103]. To illustrate, FSPs participating in a local flexibility market based on auctions and FSPs that provide flexibility by participating in a demand response program based on dynamic pricing will exploit a different business model [183]. The business model based on FSPs participating in the local auction market may have the objective of maximising their profits. At the same time, the FSPs involved in using dynamic tariffs may rely on business models that maximise the energy bill savings. In both cases, the FSPs maximises the revenue due to the flexibility provision; however, the strategy adopted is different. In general, the FSPs (e.g., consumers, prosumers, and aggregators) can be considered market players who typically participate in the electricity market to maximise their revenues or savings. Generally, the FSP's business model has to generate enough revenue to **cover the investment and operational costs that occur due to the provision of the system service**. These costs correspond to the investment and operation & maintenance costs required for enabling the flexibility provision (flexible resource, control system, ICT infrastructure for flexible devices, software license), the costs of providing the flexibility (internal power losses, comfort losses, opportunity cost corresponding to the core business losses), and, eventually the profits. As in the case of the aggregator, the business models have to be based on a **reliable estimation of the value of the flexibility provided**. Furthermore, the novelty of the topic and the lack of historical data make obtaining a reliable estimation a challenging task. However, it is worth noting that FSPs could also be motivated to provide flexibility to the power system to contribute to the energy transition, secure the operation of the network, and the local community. In that case, the profits for the flexibility provision are not monetarily remunerated but through externalities such as the positive return of image.

Whatever the adopted flexibility mechanism, flexibility's exploitation involves incurring certain unavoidable costs for system management (e.g. Distribution Management System at grid level or the home management system at building level), the engagement of the owner of the energy resources, investments in ICT [183]. Moreover, the FSP could have to invest for being capable to provide the system service (i.e. purchasing of control and monitoring equipment, smart meter upgrade). This investment cost could be charged to the network customer who owns the flexible resource depending on the regulatory framework in force and the commercial agreements. Moreover, if the provision of the system services is remunerated or compensated, there is a transfer from the DSO (the service buyer) to the FSP (the service provider). The payments from the DSO to the FSP are a monetary benefit for the FSP but represent a monetary cost for the DSO. If these transfers are not balanced, the flexibility procurement could become less economically viable for the DSO, or the provision of flexibility could be seen as not enough appealing for the FSP. Therefore, it is of utmost interest to determine the equilibrium between the DSO and the FSP perspective. The actual price assigned to the flexibility for the transfers between the DSO and the FSP has to be profitable for both the actors and pursue the highest economic efficiency. A market-based system using market prices could lead to the optimal allocation of flexibility and bring liquidity to those purposes (congestion management, balancing, portfolio optimization or retaining them for the use of the provider) where they have the greatest economic value. That is the whole purpose of flexibility markets design or other mechanisms that try to imitate market results.

As in aggregators' business model, the FSPs business models have to consider as a key partner the DSO, since a transparent relationship with the DSO would help the internal process, hence increasing the business model profitability.

The optimisation of the FSPs processes and the profitability of the service provided to the distribution system depend on the weather forecast accuracy, load projections, optimization algorithms, **and portfolio management**. However, these activities would represent very demanding tasks for the single FSP. Therefore, the business model design has to carefully define the equilibrium point between the related costs and the potential revenue to guarantee profitability depending on the FSP type (business or residential), the core business of the FSPs, and the expectation from the flexibility provision.

Table 5-8 resumes the main challenges and recommendations concerning the business models of DSOs, aggregators, and FSPs in the future distribution system.

Table 5-8. Main challenges and recommendations concerning the business models of DSOs, aggregators, and FSPs in the future distribution system

Main challenges and recommendations concerning the business models of DSOs, aggregators, and FSPs in the future distribution system are listed below. • In general, the business model design will depend on the evolution of the regulatory framework. • DSOs have to tailor their business model according to the roles covered and the corresponding responsibilities. Moreover, the business model design has to consider the flexibility procurement mechanism, the products available and the service to be acquired. A unique business model that fits all circumstances does not exist. • The DSO business model has to include clear communication with the network customers (aggregators, FSPs), it would represent a crucial added value. For example, developing effective DSO-FSP coordination allows FSPs to optimally schedule their activities, considering the network flexibility needs optimally. • The aggregators' and FSPs' business models may have to tackle the costs required for the observability and controllability of the resources. • The aggregators' and FSPs' business models have to be based on a reliable estimation of the value of the flexibility provided. • The aggregators' and FSPs' business models have to include clear communication with the DSO. • The aggregators' and FSPs' business models have to consider as key resources weather and wholesale forecast, load projections, optimization algorithms and portfolio management.

6 Conclusions

The ongoing energy transition is already affecting the electricity system; however, fundamental changes are imperative in the near future to be able to comply with the EU GHG emission objectives to be achieved in the long term. Policy drivers such as renewable sources, decentralisation of electricity generation, and electrification of the energy demand will require fundamental changes to the distribution system. Technology development such as digitalisation allows distribution network customers to become active participants who interact with the electric power system. Consumers with distributed energy resources can provide electricity back to the network by installing distributed generation and storage technologies, including electric vehicles. If adequately managed, these technologies can provide a wide range of system services and support grid planning and operation.

The present deliverable contributes to the ongoing transformation of the electricity system analysing the future EU vision from the distribution system perspective, reviewing long term national energy and climate plans of six target countries (Germany, Spain, Belgium, Portugal, Poland), identifying the technology options that will be responsible for unprecedent changes on the distribution system, and assessing the expected future scenario to understand the flexibility needs of the future distribution system. The activities described in this deliverable highlight challenges and opportunities to provide insights and recommendations from the technical, regulatory, and market perspectives to contribute to the evolution of the distribution system from now to 2050 and beyond.

This document presents high-level analyses considering the impacts to the distribution system at the system level, hence, irrespective of specific local conditions (e.g., regulation, the actual level of deployment of the technology options, the status of the grid). This analysis represents a top-down approach for identifying the distribution system needs in the long term. The aim is to identify the main aspects that have to be considered in the bottom-up quantitative approach for estimating the flexibility needs of a specific network; which, requires detailed information regarding the context and the knowledge of the grid.

This deliverable provides a long-term vision for technologies, particularly utility-scale and distributed renewable generation, storage, electric vehicles, and smart grid developments, for the EU target countries. The challenges and opportunities for system and network operators are identified under current regulatory frameworks and market rules to characterise future flexibility needs. The contributions of the present deliverable are:

- the analysis of the long-term European strategy for a carbon-neutral society (section 2.1),
- the definition of the main technology options and formalisation of a unified list (Section 2.3),
- the analysis of the long-term climate plans of the EUniversal project target countries (Germany, Spain, Belgium, Portugal, Poland) and the mapping with the technology option defined (Table 2-9),
- the identification of the technology options which can impact the distribution system (Table 3-4)
- the analysis of the high-level EU scenarios for 2050 to identify the deployment level expected for the technology options (section 4.3.1),
- the high-level appraisal of the impact that each scenario would have on the distribution system (section 4.4),
- the discussion on findings, challenges, and recommendations regarding technology options deployment, planning and operation practices, regulation for the future distribution system, business models for the actors of the future distribution system (section 5).

Analysis of the long-term vision for a carbon-neutral EU in 2050 and the long-term national plans for energy and climate

Since the transition that the electricity system is experiencing is driven by high-level policy goals, this deliverable firstly describes the long-term vision for a carbon-neutral EU in 2050. The European strategy is based on seven main action blocks: energy efficiency, deployment of renewables, sustainable mobility, circular economy, interconnection of infrastructures, carbon capture storage technologies, bio-economy and carbon sinks. Not all these action blocks directly impact the distribution system; however, the actions are intertwined, and therefore, their indirect impacts on the distribution system are investigated. The analysis of the National Energy and Climate Plans of target countries included in the EUniversal project (Belgium, Germany, Poland, Portugal and Spain) allows to identify policies and technologies expected in the future European electricity system. The most relevant technologies to achieve the national climate goals for each target country are identified for the transportation, buildings, and energy sector.

Based on scientific literature, the univocal definition of each technology option is provided to ease the communication on the related concepts and harmonise the terminology used in the different national plans, since among the national plans often the same technology option is described with different terms. One of the plan analysis contributions is mapping the national plans with the proposed definition of the technology options. Moreover, the condensed representation of the five national plans allowed to pick out similarities and differences in terms of the technology options that are expected to be adopted in the future energy system. Historical and geographical (and then climate) peculiarities influence the adoption of the technology options in the different plans. Several technology options will be developed in all countries (e.g., battery electric vehicles, heat pumps, energy efficiency measures for buildings, renewable at the household level, energy storage systems). Contrariwise, other technology options are crucial only for some of the national energy plans (e.g., large renewable power plants, CHP, biomass, heating and cooling networks). It is evident that, among the Member States, one solution does not fit all to achieve the policy and climate goals.

The vision for a carbon-neutral EU in 2050 and the relevant national energy and climate plans for the target countries are discussed in chapter 2: The long-term vision for a carbon-neutral EU in 2050.

Analysis of the technology options considering their impact on the distribution system

The technology options are assessed individually to point out the potential impact on the distribution system. The proposed high-level analysis considers the impacts to the distribution system at the system level, it is, therefore, scenario and grid agnostic. This analysis aims to identify the main aspects that have to be considered in quantitative estimations of the flexibility needs, which, in turn, requires detailed information regarding the context (e.g. regulation, scenario) and the knowledge of the grid (e.g., the status of the network, zonal load and generation type and capacity).

The criteria adopted to identify the relevant technology options are the connection to the distribution grid, the asset typology (load, generator, or both), the capability to generate bidirectional electric power flows, the ability to provide short-term flexibility. The corresponding impact on the distribution system is then classified considering two attributes that describe if the technology option affects the planning stage, the operation stage, or both, and if the impact is direct (i.e. it concerns connected resources) or indirect (i.e., the technology option affects the distribution system through the effects caused by synergic or competing technology options). The outcome of this assessment is a subset of technology options that can impact the future distribution system. However, to estimate each technology option's impact on the distribution system, the characteristics of the expected future scenario have to be considered since they define the level of deployment expected for each technology option. The analysis of the most relevant future scenarios is performed concerning the level of development expected for each technology option in the different scenario paths.

The analysis of the relevant technology options is discussed in chapter 3: Analysis of the technology options considering the impact on the distribution system.

Analysis of the flexibility needs in long-term scenarios

The analysis of scenario paths performed focuses on the ones defined by the European Commission for the *Clean Planet for All* package [1]. The proposed scenarios have the 2050 horizon and are developed to reach a carbon-neutral society. The analysed scenarios are ELEC, H2, P2X, and EE since they define the highest stress conditions for the distribution system. Each of these scenarios expects to reach the policy goals relying on a specific strategy: the ELEC scenario is based on the electrification of the energy demand, the EE scenario on the adoption of energy efficiency measures, the H2 and P2X scenario promote the use of hydrogen and power-to-x technologies respectively. Each scenario is analysed to determine the technology options adopted and understand their corresponding deployment level. Then, considering each technology option independently, the impact on the distribution system in terms of the residual flexibility needs is studied considering the four following factors: electricity demand increase, an increase of generation from renewable sources, the increase of generation at the distribution level, and the increase of technology options able to provide flexibility. The first three factors relate to the increase of the flexibility needs of the distribution system, while the latter factor determines by itself a reduction of the need for flexibility in the distribution system.

The assessment of the flexibility needs in long-term scenarios is discussed in chapter 4: Flexibility needs in long-term scenarios.

Challenges and recommendations concerning technology option deployment

The findings of the scenario analysis point out that the main technology options to be considered for the related impact in the distribution system are the battery electric vehicles, heat pumps, building refurbishment, an increase of renewable generation at the household level, CHP, and building automation. Moreover, the scenario analysis highlights that estimating quantitatively the impacts of the technology options on the distribution system requires complementing the information available from the scenarios proposed for the European Union in [2] with local information, particularly by estimating the quota of local generation expected to be connected in the distribution system, the deployment of CHP, and the adoption of building automation technologies. Reliable information on these technology options can be available only at the local level, in line with the requirements for moving from the high-level to the quantitative estimation of the impacts. Therefore, it is evident that assessing the flexibility needs for the future distribution system requires both a top-down and a bottom-up approach. The top-down qualitative approach, as the analyses presented in this document, allows understanding the objective to be achieved, the boundaries of the strategies, and the high-level challenges. The top-down approach guides the bottom-up approach that exploits local information such as the actual level of deployment of the technology options and knowledge of the grid (e.g., the status of the network, zonal load and generation type and capacity) to determine quantitatively the flexibility need of a specific distribution network and the already available flexible resources.

The analysis of the long-term vision for a carbon-neutral EU in 2050 and the national energy and climate plans, the study of the technology options and the future scenarios expected in the EU allow identifying the main challenges and formalising a set of general recommendations to guide the evolution of the distribution system. These recommendations concern the technology option deployment to take full advantage of the changes expected for the distribution system, approaches and tools for future distribution system planning and operation resorting flexible resources. Moreover, the recommendations regard the flexibility procurement mechanism to be adopted and the required evolution of regulation and business models for the future distribution system.

The findings and recommendations concerning technology option development are discussed in section 5.1: Discussion on the future deployment of the technology options**Error! Reference source not found.**.

Challenges and recommendations on planning and operation for the future distribution system

As pointed out by the study of the future EU scenarios, operating and planning the future distribution system are subject to high uncertainties, mostly due to the various possible technology options deployed and the various operational schemas that could be adopted in the long term. As discussed, the high-level analysis of the impact on the distribution system sets the basis for a more detailed analysis to be addressed at the local level. The specific distribution system characteristics are highly dependent on local conditions (e.g., regulation at country level, load and generation type, capacity, and volume in the area of interest, the initial status of the network); therefore, quantitative appraisals of the future flexibility need, and the development of innovative operation and planning practices, have to resort local information. The analysis described in this report identified the technology options that should be carefully taken into account (Table 3-4), how these technology options are intertwined (Table 3-2), and how the deployment of the different policy perspectives for the energy system of the future influence the technology option deployment and the related impact on the distribution system (Table 4-4, Table 4-5, Table 4-6). Load and generation profiling and forecasting require to be enhanced in temporal and spatial accuracy. Forecasting of load, generation and flexibility become essential for distribution system operation and consequently for planning. Therefore, continuous forecast quality and availability assessment are needed for cost-effective and resilient operation and planning in the future distribution system. Long-term planning scenarios need to consider the degree of decentralisation of DER and the corresponding CAPEX and OPEX for ICT needed to coordinate a highly distributed system with very high security of supply and cybersecurity requirements. Realistic large-scale distribution system models, so-called Reference Network Models (RNM) should be used to validate complex active network operation and planning. The accuracy of the distribution network models used for network studies has to increase, the future network models have to be the digital twins of the real network.

The findings and recommendations for quantitative assessment of flexibility needs are discussed in section 5.2: Discussion on the challenges of operation and planning of future distribution networks.

Challenges and recommendations on procurement mechanisms for the future distribution system

As highlighted by the scenario and technology option analysis, all scenarios concern developing technology options capable of providing system services to the DSO. Deliverable D3.1 "Flexibility Toolbox" describes the different technologies that could provide flexibility in the distribution and transmission system, such as different storage technologies and demand-side flexibility [118]. DSOs can use a wide range of mechanisms to acquire flexibility from resources owned by other players of the distribution systems (e.g., distributed generators, prosumers, customers, aggregators). Any mechanism for acquiring system services shall aim for technology neutrality, as discussed in EUniversal Deliverable 5.1 [103]. The key mechanisms of interest among the ones discussed in EUniversal Task 5.1 are: flexible access and connection agreements, dynamic network tariffs and local flexibility markets [103]. Flexibility markets should be preferred unless the context makes them impossible. Moreover, the local characteristics have to be carefully assessed to ensure enough liquidity and prevent market distortions. Dynamic network tariffs and connection agreements could easily involve small business and residential customers in providing flexibility since the lower complexity perceived by the final electricity users.

The findings and recommendations on procurement mechanisms for the future distribution system are discussed in section 5.3: Discussion on the flexibility procurement mechanisms.

Challenges and recommendations for regulation in future distribution energy systems

The review of the EU long term vision and scenarios and the analysis of the possible technology options point out the tremendous transformation required to the distribution system. Modernisation of regulation has to accompany the energy transition and distribution system evolution, taking advantage of the available opportunities without jeopardising supply quality and security and increasing overall system costs. Since the novelty of procuring system services from third-party resources connected to the distribution system, design such local mechanisms is pioneering and requires regulatory experimentation to explore all possible mechanisms, local conditions, and assess the related strengths and weaknesses. Regulatory experimentation may help the NRA and DSOs to obtain evidence that helps to elaborate the regulations needed for implementing the future flexibility procurement mechanisms. To this aim, regulatory sandboxes are legislation instruments to experiment with innovative business models or technologies, which under normal conditions would be hindered by legal or regulatory barriers [143]. They provide an experimental environment to foster innovation and business model development. Moreover, it is highlighted the need for innovative decision-making support to appraise projects that include traditional network planning and flexibility resources considering more aspects than only the monetary ones. The main challenges to be addressed by regulation experimentation regard market integration, project appraisal, distribution network planning, flexibility remuneration, and TSO-DSO coordination.

The findings and recommendations for regulation in future distribution energy systems are discussed in section 5.4: Discussion on regulation for the future distribution system.

Challenges and recommendations for business models in future distribution energy systems

The analysis of the EU long-term scenarios and the corresponding level deployment of the technology options make evident that the evolution of the distribution system implies the emergence of new actors, new business models, and changes in the business models of the existing electricity actors depending on covered roles and assigned responsibilities. Regarding the DSO, its role depends on the responsibilities for ensuring the security and quality of the electricity supply and the requirements to guarantee universal access to the grid to the other electricity sector actors. The business model of the DSO changes if the grid ownership and the grid operation are assigned to different entities, if the DSO also covers the role of the local market operator, and if the DSO plays the role of the energy manager for the local energy community.

Regarding FSPs, the adopted business model and the related characteristics (e.g., value proposition, key activities, key partners, cost structure, revenue streams) would depend on the flexibility procurement mechanism in place (e.g. obligation, network tariffs, connection agreements, or market-based procedures) and the service provided [103]. In fact, the flexibility procurement mechanism defines the rules, process, and remuneration of the flexibility provision. The procurement process determines the limits of the business opportunities and the possible revenue streams. Furthermore, the aggregator may play a central role in flexibility procurement [176]. The aggregator is an emerging actor in energy systems that aggregates energy production and consumption from different sources (e.g., generators, loads, storage) and acts toward the grid as one entity [178], [184]. Innovation in regulation is needed to clarify its role and its interactions with the other agents. Aggregators are market players with a revenue-oriented business model. Also, the aggregator's business model characteristics depend on the regulation in force and the mechanism for procuring system services that influence the revenue stream.

The findings and recommendations for business models in future distribution energy systems are discussed in section 5.5: Discussion on business models for DSO, aggregators, and FSPs.

Correlation within the EUniversal project

The present deliverable highlights challenges and opportunities for grids and markets considering the long-term scenarios for the distribution system. The activities of this deliverable follow the review of recent and ongoing policy and regulatory initiatives (EUniversal Task 1.1); draw lessons learnt from recent and ongoing research and demonstration initiatives relevant to the project objectives which the set of the grid and non-grid DSO needs and the respective services are identified (EUniversal Task 1.2). Moreover, Deliverable 1.3 builds further on the experience of EUniversal D5.1 in which relevant market mechanisms for the procurement of flexibility needs and grid services are determined, and EUniversal D2.2 that describes the use cases and roles & responsibilities of the different actors for the EUniversal demos.

This deliverable provides a long-term vision for technologies, particularly utility-scale and distributed renewable generation, storage, electric vehicles, and smart grid developments, for the EU target countries (Germany, Spain, Belgium, Portugal, Poland). The challenges and opportunities for system and network operators are identified under current regulatory frameworks and market rules to characterise future flexibility needs. The achievements mentioned above serve as an input to WP4, WP5 and WP10, where best practices and detailed recommendations for new business models, market arrangements and regulatory mechanisms are provided.

This deliverable aims to contribute to the following activities of the EUniversal project:

- Task 4.2 is focused on long-term scenarios that can guide exploitation and roadmaps definition with the inputs regarding the technology option scenario analysis and the challenges on operation and planning of distribution network.
- Task 5.4 concerns market mechanisms assessment from the multi-stakeholder perspective with the identified challenges and opportunities for system operators.
- Task 10.1 examines the current practice and future target model of distribution network planning, focusing on the trade-off between flexibility and network investments and business model canvas analysis of the different demo projects.
- Task 10.2, focused on regulation, will study in detail the regulatory sandboxes, and it will benefit from the scenario analysis and the identification of the relevant challenges.
- Task 10.3 and Task 10.4, focused and scalability, replicability and roadmap formalisation, will benefit from the scenario analysis and the identification of the main technology options.

Bibliography

[1] European Commission, "COM (2018) 773 final, A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy," Nov. 28, 2018. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52018DC0773 (accessed Dec. 10, 2020).

[2] European Commission, "In-depth analysis in support on the COM (2018) 773: A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy | Knowledge for policy," Nov. 2018. Accessed: Dec. 10, 2020. [Online]. Available: https://knowledge4policy.ec.europa.eu/publication/depth-analysis-support-com2018-773-clean-planet-all-european-strategic-long-term-vision_en

[3] United Nations Framework Convention on Climate Change (UNFCCC), *The Paris Agreement*. United Nations, 2015. Accessed: Dec. 30, 2020. [Online]. Available: https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[4] F. Pilo, S. Jupe, F. Silvestro, C. Abbey, A. Baitch, B. Bak-Jensen, C. Carter-Brown, G. Celli, K. ElBakari, M. Fan, P. Georgilakis, T. Hearne, L. N. Ochoa, G. Petretto and J. Taylor, (last), "Planning and optimization methods for active distribution systems," CIGRE, Paris, 2016. [Online]. Available: https://e-cigre.org/publication/ELT_276_7-planning-and-optimization-methods-for-active-distribution-systems

[5] E. Hillberg *et al.*, "Flexibility needs in the future power system," *Int. Smart Grid Action Netw. - ISGAN Annex 6*, 2019, doi: 10.13140/RG.2.2.22580.71047.

[6] International Renewable Energy Agency (IRENA), "Power system flexibility for the energy transition, Part 1: Overview for policy makers," 2018, [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Nov/IRENA_Power_system_flexibility_1_2018.pdf

[7] International Energy Agency (IEA), "Status of Power System Transformation 2019 - Power System Flexibility," *IEA Webstore*, 2019, [Online]. Available: https://webstore.iea.org/status-of-power-system-transformation-2019

[8] A. Keane *et al.*, "State-of-the-Art Techniques and Challenges Ahead for Distributed Generation Planning and Optimization," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1493–1502, May 2013, doi: 10.1109/TPWRS.2012.2214406.

[9] F. Pilo, G. Celli, E. Ghiani, and G. G. Soma, "New Electricity Distribution Network Planning Approaches for Integrating Renewables," in *Advances in Energy Systems*, John Wiley & Sons, Ltd, 2019, pp. 167–186. doi: 10.1002/9781119508311.ch10.

[10] International Energy Agency (IEA), "Status of Power System Transformation 2018 - Advanced Power Plant Flexibility," *IEA Webstore*, 2018, [Online]. Available: https://webstore.iea.org/status-of-power-system-transformation-2018

[11] CEDEC, EDSO for Smart Grids, Eurelectric, Eurogas, GEODE, "Flexibility in the energy transition a toolbox for electricity DSOs," 2018, Accessed: Dec. 30, 2020. [Online]. Available: https://www.edsoforsmartgrids.eu/flexibility-in-the-energy-transition-a-toolbox-for-electricity-dsos/

[12] Croatian Presidency of the Council of the European Union, "Submission by Croatia and the European Commission on behalf of the European Union and its Member States - Long-term low greenhouse gas emission development strategy of the European Union and its Member States," Jun. 03, 2020. https://unfccc.int/sites/default/files/resource/HR-03-06-2020%20EU%20Submission%20on%20Long%20term%20strategy.pdf (accessed Dec. 10, 2020).

[13] "Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council (Text with EEA relevance.)," 32018R1999, Dec. 2018. Accessed: Dec. 10, 2020. [Online]. Available: http://data.europa.eu/eli/reg/2018/1999/oj/eng

[14] European Union; Publications Office of the European Union, "Going climate-neutral by 2050 : a strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy.," Jul. 16, 2019. http://op.europa.eu/en/publication-detail/-/publication/92f6d5bc-76bc-11e9-9f05-01aa75ed71a1 (accessed Dec. 11, 2020).

[15] "A European Green Deal," *European Commission - European Commission*. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed Jul. 20, 2021).

[16] "Delivering the European Green Deal," *European Commission - European Commission*. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en (accessed Jul. 20, 2021).

[17] P. O. of the E. U. European Un, "Bioeconomy : the European way to use our natural resources : action plan 2018.," Jan. 28, 2019. http://op.europa.eu/en/publication-detail/-/publication/775a2dc7-2a8b-11e9-8d04-01aa75ed71a1 (accessed Dec. 11, 2020).

[18] European Commission, "EU National energy and climate plans," *European NECPs*. https://ec.europa.eu/info/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en (accessed Dec. 11, 2020).

[19] European Commission, "European Commission - National long-term strategies," *European Commission - National long-term strategies*. https://ec.europa.eu/info/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-long-term-strategies_en (accessed Dec. 11, 2020).

[20] M. A. Katouzian, "The Development of the Service Sector: A New Approach," *Oxf. Econ. Pap.*, vol. 22, no. 3, pp. 362–382, 1970.

[21] P. Nieuwenhuis, L. Cipcigan, and H. Berkem Sonder, "11 - The Electric Vehicle Revolution," in *Future Energy (Third Edition)*, T. M. Letcher, Ed. Elsevier, 2020, pp. 227–243. doi: 10.1016/B978-0-08-102886-5.00011-6.

[22] J. A. Sanguesa, V. Torres-Sanz, P. Garrido, F. J. Martinez, and J. M. Marquez-Barja, "A Review on Electric Vehicles: Technologies and Challenges," *Smart Cities*, vol. 4, no. 1, Art. no. 1, Mar. 2021, doi: 10.3390/smartcities4010022.

[23] S. Jain and L. Kumar, "31 - Fundamentals of Power Electronics Controlled Electric Propulsion," in *Power Electronics Handbook (Fourth Edition)*, M. H. Rashid, Ed. Butterworth-Heinemann, 2018, pp. 1023–1065. doi: 10.1016/B978-0-12-811407-0.00035-0.

[24] B. G. Pollet, I. Staffell, J. L. Shang, and V. Molkov, "22 - Fuel-cell (hydrogen) electric hybrid vehicles," in *Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance*, R. Folkson, Ed. Woodhead Publishing, 2014, pp. 685–735. doi: 10.1533/9780857097422.3.685.

[25] J. M. German, "Hybrid Electric Vehicles," in *Encyclopedia of Energy*, C. J. Cleveland, Ed. New York: Elsevier, 2004, pp. 197–213. doi: 10.1016/B0-12-176480-X/00180-7.

[26] D. Gonzales, E. M. Searcy, and S. D. Ekşioğlu, “Cost analysis for high-volume and long-haul transportation of densified biomass feedstock,” *Transp. Res. Part Policy Pract.*, vol. 49, pp. 48–61, Mar. 2013, doi: 10.1016/j.tra.2013.01.005.

[27] V. Reis and R. Macário, “Chapter 3 - Introduction to freight transport chains,” in *Intermodal Freight Transportation*, V. Reis and R. Macário, Eds. Elsevier, 2019, pp. 43–70. doi: 10.1016/B978-0-12-814464-0.00003-7.

[28] P. Aditjandra, “Chapter Two - Review of international journey planning system to welcoming MaaS,” in *Advances in Transport Policy and Planning*, vol. 3, E. Ben-Elia, Ed. Academic Press, 2019, pp. 29–47. doi: 10.1016/bs.atpp.2019.07.001.

[29] P. Tranter and R. Tolley, “Chapter 10 - A new vision for the city: transforming behaviours, values and cultures,” in *Slow Cities*, P. Tranter and R. Tolley, Eds. Elsevier, 2020, pp. 315–353. doi: 10.1016/B978-0-12-815316-1.00010-1.

[30] C. Roncoli, M. Papageorgiou, and I. Papamichail, “Traffic flow optimisation in presence of vehicle automation and communication systems – Part II: Optimal control for multi-lane motorways,” *Transp. Res. Part C Emerg. Technol.*, vol. 57, pp. 260–275, Aug. 2015, doi: 10.1016/j.trc.2015.05.011.

[31] M. Makridis, K. Mattas, C. Mogno, B. Ciuffo, and G. Fontaras, “The impact of automation and connectivity on traffic flow and CO2 emissions. A detailed microsimulation study,” *Atmos. Environ.*, vol. 226, p. 117399, Apr. 2020, doi: 10.1016/j.atmosenv.2020.117399.

[32] E. Fishman, S. Washington, and N. Haworth, “Bike share’s impact on car use: Evidence from the United States, Great Britain, and Australia,” *Transp. Res. Part Transp. Environ.*, vol. 31, pp. 13–20, Aug. 2014, doi: 10.1016/j.trd.2014.05.013.

[33] E. Eren and V. E. Uz, “A review on bike-sharing: The factors affecting bike-sharing demand,” *Sustain. Cities Soc.*, vol. 54, p. 101882, Mar. 2020, doi: 10.1016/j.scs.2019.101882.

[34] S. Ataç, N. Obrenović, and M. Bierlaire, “Vehicle sharing systems: A review and a holistic management framework,” *EURO J. Transp. Logist.*, vol. 10, p. 100033, Jan. 2021, doi: 10.1016/j.ejtl.2021.100033.

[35] S. Schmöller and K. Bogenberger, “Chapter 11 - Carsharing: An overview on what we know,” in *Demand for Emerging Transportation Systems*, C. Antoniou, D. Efthymiou, and E. Chaniotakis, Eds. Elsevier, 2020, pp. 211–226. doi: 10.1016/B978-0-12-815018-4.00011-5.

[36] F. Ferrero, G. Perboli, M. Rosano, and A. Vesco, “Car-sharing services: An annotated review,” *Sustain. Cities Soc.*, vol. 37, pp. 501–518, Feb. 2018, doi: 10.1016/j.scs.2017.09.020.

[37] T. Konstantinou and U. Knaack, “Refurbishment of Residential Buildings: A Design Approach to Energy-Efficiency Upgrades,” *Procedia Eng.*, vol. 21, pp. 666–675, Jan. 2011, doi: 10.1016/j.proeng.2011.11.2063.

[38] K. Arning, E. Dütschke, J. Globisch, and B. Zaunbrecher, “Chapter 2.2 - The challenge of improving energy efficiency in the building sector: Taking an in-depth look at decision-making on investments in energy-efficient refurbishments,” in *Energy and Behaviour*, M. Lopes, C. H. Antunes, and K. B. Janda, Eds. Academic Press, 2020, pp. 129–151. doi: 10.1016/B978-0-12-818567-4.00002-8.

[39] M. Moldovan, I. Visa, and A. Duta, “20 - Future trends for solar energy use in nearly zero energy buildings,” in *Advances in Solar Heating and Cooling*, R. Z. Wang and T. S. Ge, Eds. Woodhead Publishing, 2016, pp. 547–569. doi: 10.1016/B978-0-08-100301-5.00020-5.

[40] M. Lu and J. H. K. Lai, “Building energy: a review on consumptions, policies, rating schemes and standards,” *Energy Procedia*, vol. 158, pp. 3633–3638, Feb. 2019, doi: 10.1016/j.egypro.2019.01.899.

[41] E. Rodriguez-Ubinas *et al.*, "Passive design strategies and performance of Net Energy Plus Houses," *Energy Build.*, vol. 83, pp. 10–22, Nov. 2014, doi: 10.1016/j.enbuild.2014.03.074.

[42] D.-T. Bălănescu and V.-M. Homutescu, "Study on condensing boiler technology potential accounting various fuels," *Procedia Manuf.*, vol. 32, pp. 504–512, Jan. 2019, doi: 10.1016/j.promfg.2019.02.246.

[43] J. Gong and K. Sumathy, "9 - Active solar water heating systems," in *Advances in Solar Heating and Cooling*, R. Z. Wang and T. S. Ge, Eds. Woodhead Publishing, 2016, pp. 203–224. doi: 10.1016/B978-0-08-100301-5.00009-6.

[44] K. Hudon, "Chapter 20 - Solar Energy – Water Heating," in *Future Energy (Second Edition)*, T. M. Letcher, Ed. Boston: Elsevier, 2014, pp. 433–451. doi: 10.1016/B978-0-08-099424-6.00020-X.

[45] A. Neave, "41 - Heat pumps and their applications," in *Plant Engineer's Reference Book (Second Edition)*, D. A. Snow, Ed. Oxford: Butterworth-Heinemann, 2002, pp. 41–1. doi: 10.1016/B978-075064452-5/50096-1.

[46] B. Bharathiraja, T. Sudharsanaa, A. Bharghavi, J. Jayamuthunagai, and R. Praveenkumar, "Biohydrogen and Biogas – An overview on feedstocks and enhancement process," *Fuel*, vol. 185, pp. 810–828, Dec. 2016, doi: 10.1016/j.fuel.2016.08.030.

[47] S. Ahuja, "1 - Nexus of Food, Energy, and Water," in *Food, Energy, and Water*, S. Ahuja, Ed. Boston: Elsevier, 2015, pp. 1–20. doi: 10.1016/B978-0-12-800211-7.00001-6.

[48] C. J. Cleveland and C. Morris, Eds., "S," in *Dictionary of Energy (Second Edition)*, Boston: Elsevier, 2015, pp. 515–583. doi: 10.1016/B978-0-08-096811-7.50019-6.

[49] N. Rajalakshmi, R. Balaji, and S. Ramakrishnan, "14 - Recent developments in hydrogen fuel cells: Strengths and weaknesses," in *Sustainable Fuel Technologies Handbook*, S. Dutta and C. Mustansar Hussain, Eds. Academic Press, 2021, pp. 431–456. doi: 10.1016/B978-0-12-822989-7.00015-9.

[50] M. M. Martín, "Chapter 5 - Syngas," in *Industrial Chemical Process Analysis and Design*, M. M. Martín, Ed. Boston: Elsevier, 2016, pp. 199–297. doi: 10.1016/B978-0-08-101093-8.00005-7.

[51] M. Börjesson and E. O. Ahlgren, "5.07 - Biomass CHP Energy Systems: A Critical Assessment," in *Comprehensive Renewable Energy*, A. Sayigh, Ed. Oxford: Elsevier, 2012, pp. 87–97. doi: 10.1016/B978-0-08-087872-0.00508-4.

[52] L. Jörissen, "APPLICATIONS – STATIONARY | Residential Energy Supply: Fuel Cells," in *Encyclopedia of Electrochemical Power Sources*, J. Garche, Ed. Amsterdam: Elsevier, 2009, pp. 108–123. doi: 10.1016/B978-044452745-5.00346-4.

[53] M. Gambini and M. Vellini, "High Efficiency Cogeneration: Performance Assessment of Industrial Cogeneration Power Plants," *Energy Procedia*, vol. 45, pp. 1255–1264, Jan. 2014, doi: 10.1016/j.egypro.2014.01.131.

[54] M. Gambini and M. Vellini, "High Efficiency Cogeneration: Electricity from Cogeneration in CHP Plants," *Energy Procedia*, vol. 81, pp. 430–439, Dec. 2015, doi: 10.1016/j.egypro.2015.12.117.

[55] M. Vellini, M. Gambini, and T. Stilo, "High-efficiency cogeneration systems for the food industry," *J. Clean. Prod.*, vol. 260, p. 121133, Jul. 2020, doi: 10.1016/j.jclepro.2020.121133.

[56] M. Sugiyama, "Climate change mitigation and electrification," *Energy Policy*, vol. 44, pp. 464–468, May 2012, doi: 10.1016/j.enpol.2012.01.028.

[57] Ashok Kumar L., Indragandhi V., and Uma Maheswari Y., "Chapter 9 - PVSYST," in *Software Tools for the Simulation of Electrical Systems*, Ashok Kumar L., Indragandhi V., and Uma Maheswari Y., Eds. Academic Press, 2020, pp. 349–392. doi: 10.1016/B978-0-12-819416-4.00009-0.

[58] B. Loganathan, H. Chowdhury, I. Mustary, M. M. Rana, and F. Alam, "Design of a micro wind turbine and its economic feasibility study for residential power generation in built-up areas," *Energy Procedia*, vol. 160, pp. 812–819, Feb. 2019, doi: 10.1016/j.egypro.2019.02.153.

[59] T. Forsyth and F. Oteri, "Chapter Twelve - Distributed Wind Systems: Promoting Growth of Small Wind Systems," in *Small Wind*, R. N. Clark, Ed. Boston: Academic Press, 2014, pp. 179–188. doi: 10.1016/B978-0-12-385999-0.00012-6.

[60] R. N. Clark, "Chapter Thirteen - The Future of Small Wind: Factors That May or May Not Affect the Growth of Small Wind," in *Small Wind*, R. N. Clark, Ed. Boston: Academic Press, 2014, pp. 189–195. doi: 10.1016/B978-0-12-385999-0.00013-8.

[61] S. Jaisankar, J. Ananth, S. Thulasi, S. T. Jayasuthakar, and K. N. Sheeba, "A comprehensive review on solar water heaters," *Renew. Sustain. Energy Rev.*, vol. 15, no. 6, pp. 3045–3050, Aug. 2011, doi: 10.1016/j.rser.2011.03.009.

[62] P. Domingues, P. Carreira, R. Vieira, and W. Kastner, "Building automation systems: Concepts and technology review," *Comput. Stand. Interfaces*, vol. 45, pp. 1–12, Mar. 2016, doi: 10.1016/j.csi.2015.11.005.

[63] V. Vasyutynskyy, J. Ploennigs, and K. Kabitzsch, "Passive Monitoring of Control Loops in Building Automation," in *Fieldbus Systems and Their Applications 2005*, M. L. Chávez, Ed. Oxford: Elsevier, 2006, pp. 263–269. doi: 10.1016/B978-008045364-4/50076-9.

[64] M. Balboa-Fernández, M. de Simón-Martín, A. González-Martínez, and E. Rosales-Asensio, "Analysis of District Heating and Cooling systems in Spain," *Energy Rep.*, vol. 6, pp. 532–537, Dec. 2020, doi: 10.1016/j.egyr.2020.11.202.

[65] A. Vandermeulen, B. van der Heijde, and L. Helsen, "Controlling district heating and cooling networks to unlock flexibility: A review," *Energy*, vol. 151, pp. 103–115, May 2018, doi: 10.1016/j.energy.2018.03.034.

[66] D. Wang *et al.*, "Integrated demand response in district electricity-heating network considering double auction retail energy market based on demand-side energy stations," *Appl. Energy*, vol. 248, Aug. 2019, doi: 10.1016/j.apenergy.2019.04.050.

[67] L. De Rosa *et al.*, "Integrated models for electrical distribution network planning and district-scale building energy use," presented at the 14th PowerTech Conference - PowerTech 2021, Madrid, Spain, Jul. 2021.

[68] P. Seferlis, P. S. Varbanov, A. I. Papadopoulos, H. H. Chin, and J. J. Klemeš, "Sustainable design, integration, and operation for energy high-performance process systems," *Energy*, vol. 224, p. 120158, Jun. 2021, doi: 10.1016/j.energy.2021.120158.

[69] Y. Xu, C. Yan, H. Liu, J. Wang, Z. Yang, and Y. Jiang, "Smart energy systems: A critical review on design and operation optimization," *Sustain. Cities Soc.*, vol. 62, p. 102369, Nov. 2020, doi: 10.1016/j.scs.2020.102369.

[70] I. Dincer and A. Abu-Rayash, "Chapter 5 - Community energy systems," in *Energy Sustainability*, I. Dincer and A. Abu-Rayash, Eds. Academic Press, 2020, pp. 101–118. doi: 10.1016/B978-0-12-819556-7.00005-X.

[71] B. P. Koirala, E. Koliou, J. Friege, R. A. Hakvoort, and P. M. Herder, "Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems," *Renew. Sustain. Energy Rev.*, vol. 56, pp. 722–744, Apr. 2016, doi: 10.1016/j.rser.2015.11.080.

[72] M. Galici *et al.*, "Energy Blockchain for Public Energy Communities," *Appl. Sci.*, vol. 11, no. 8, p. 3457, Apr. 2021, doi: 10.3390/app11083457.

[73] G. Buffo, P. Marocco, D. Ferrero, A. Lanzini, and M. Santarelli, "Chapter 15 - Power-to-X and power-to-power routes," in *Solar Hydrogen Production*, F. Calise, M. D. D'Accadia, M. Santarelli, A.

Lanzini, and D. Ferrero, Eds. Academic Press, 2019, pp. 529–557. doi: 10.1016/B978-0-12-814853-2.00015-1.

[74] Z. Chehade, C. Mansilla, P. Lucchese, S. Hilliard, and J. Proost, "Review and analysis of demonstration projects on power-to-X pathways in the world," *Int. J. Hydrog. Energy*, vol. 44, no. 51, pp. 27637–27655, Oct. 2019, doi: 10.1016/j.ijhydene.2019.08.260.

[75] F. V. Vázquez *et al.*, "Power-to-X technology using renewable electricity and carbon dioxide from ambient air: SOLETAIR proof-of-concept and improved process concept," *J. CO2 Util.*, vol. 28, pp. 235–246, Dec. 2018, doi: 10.1016/j.jcou.2018.09.026.

[76] IRENA, "Innovation landscape brief: Renewable power-to-heat," International Renewable Energy Agency, Abu Dhabi, 2019.

[77] H. Rudnick and L. Barroso, "Flexibility Needed: Challenges for Future Energy Storage Systems [Guest Editorial]," *IEEE Power Energy Mag.*, vol. 15, no. 5, pp. 12–19, Sep. 2017, doi: 10.1109/MPE.2017.2708810.

[78] A. H. Fathima and K. Palanisamy, "8 - Renewable systems and energy storages for hybrid systems," in *Hybrid-Renewable Energy Systems in Microgrids*, A. H. Fathima, N. Prabaharan, K. Palanisamy, A. Kalam, S. Mekhilef, and Jackson. J. Justo, Eds. Woodhead Publishing, 2018, pp. 147–164. doi: 10.1016/B978-0-08-102493-5.00008-X.

[79] H. Abdi, B. Mohammadi-ivatloo, S. Javadi, A. R. Khodaei, and E. Dehnavi, "Chapter 7 - Energy Storage Systems," in *Distributed Generation Systems*, G. B. Gharehpetian and S. M. Mousavi Agah, Eds. Butterworth-Heinemann, 2017, pp. 333–368. doi: 10.1016/B978-0-12-804208-3.00007-8.

[80] E. Ghiani and G. Pisano, "Chapter 2 - Impact of Renewable Energy Sources and Energy Storage Technologies on the Operation and Planning of Smart Distribution Networks," in *Operation of Distributed Energy Resources in Smart Distribution Networks*, K. Zare and S. Nojavan, Eds. Academic Press, 2018, pp. 25–48. doi: 10.1016/B978-0-12-814891-4.00002-3.

[81] J. Iqbal, F. M. Howari, A.-M. O. Mohamed, and E. K. Paleologos, "Chapter 20 - Assessment of radiation pollution from nuclear power plants," in *Pollution Assessment for Sustainable Practices in Applied Sciences and Engineering*, A.-M. O. Mohamed, E. K. Paleologos, and F. M. Howari, Eds. Butterworth-Heinemann, 2021, pp. 1027–1053. doi: 10.1016/B978-0-12-809582-9.00020-7.

[82] P. Breeze, "Chapter 6 - Combined Heat and Power," in *Power Generation Technologies (Third Edition)*, P. Breeze, Ed. Newnes, 2019, pp. 121–143. doi: 10.1016/B978-0-08-102631-1.00006-7.

[83] N. Belyakov, "Chapter Twenty-Two - Can we build a sustainable power generation system?," in *Sustainable Power Generation*, N. Belyakov, Ed. Academic Press, 2019, pp. 521–538. doi: 10.1016/B978-0-12-817012-0.00037-2.

[84] R. L. Whiting, "CHAPTER 14 - GAS FROM CONVENTIONAL GAS FIELDS," in *The Future Supply of Nature-Made Petroleum and Gas*, R. F. Meyer, J. Barnea, and M. Grenon, Eds. Pergamon, 1977, pp. 277–293. doi: 10.1016/B978-0-08-021735-2.50024-0.

[85] M. A. Hersh, "The Economics and Politics of Energy Generation," in *Improving Stability in Developing Nations through Automation 2006*, P. Kopacek, Ed. Oxford: Elsevier, 2006, pp. 77–82. doi: 10.1016/B978-008045406-1/50011-2.

[86] P. Gonzalez, "Energy Use, Human," in *Encyclopedia of Biodiversity (Second Edition)*, S. A. Levin, Ed. Waltham: Academic Press, 2013, pp. 250–266. doi: 10.1016/B978-0-12-384719-5.00242-2.

[87] Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), "Climate Action Plan 2050 – Principles and goals of the German government's climate policy," *Publ. Bundesregier.*, p. 92.

[88] Ministerio para la Transición Ecológica y el Reto Demográfico, "Estrategia de descarbonización a largo plazo 2050 - Estrategia a largo plazo para una economía española moderna, competitiva y climáticamente neutra en 2050," *Marco Estratég. Energ. Clima Una Opor.*

Para Mod. Econ. Esp. Creac. Empl., 2020, Accessed: Jan. 19, 2021. [Online]. Available: https://ec.europa.eu/clima/sites/lts/lts_es_es.pdf

[89] National Climate Commission, "Stratégie à long terme de la Belgique," 2020, Accessed: Jan. 19, 2021. [Online]. Available: https://ec.europa.eu/clima/sites/lts/lts_be_fr.pdf

[90] National Climate Commission, "Belgische Langetermijnstrategie," 2020, Accessed: Jan. 19, 2021. [Online]. Available: https://ec.europa.eu/clima/sites/lts/lts_be_nl.pdf

[91] Ministerium of the Environment and Energy Transition, "Roadmap for carbon neutrality 2050 (rnc2050) long-term strategy for carbon neutrality of the portuguese economy by 2050," 2020, Accessed: Jan. 19, 2021. [Online]. Available: https://ec.europa.eu/clima/sites/lts/lts_pt_en.pdf

[92] Ministry of National Assets - Poland, "The National Energy and Climate Plan for 2021-2030 Objectives and targets, and policies and measures," 2019, Accessed: Jan. 19, 2021. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/pl_final_necp_main_pl.pdf

[93] Hydrogen IEA TCP, "Annual Reports," *Hydrogen TCP*, 2020. https://www.ieahydrogen.org/annual-reports/ (accessed Jul. 28, 2021).

[94] International Energy Agency (IEA), Paris, "Hydrogen Tracking Report," 2020. https://www.iea.org/reports/hydrogen (accessed Jul. 28, 2021).

[95] IRENA, "Global energy transformation: A roadmap to 2050 (2019 edition)." International Renewable Energy Agency, Abu Dhabi. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_2019.pdf

[96] European Commission, "Ecodesign Impact Accounting, Overview Report 2017," 2017. Accessed: Jul. 01, 2021. [Online]. Available: https://ec.europa.eu/energy/sites/default/files/documents/eia_overview_report_2017_-_v20171222.pdf

[97] European Technology Platform on Renewable Heating and Cooling *et al.*, *2020-2030-2050, common vision for the renewable heating and cooling sector in Europe*. LU: Publications Office of the European Union, 2011. Accessed: Jul. 01, 2021. [Online]. Available: https://data.europa.eu/doi/10.2788/20474

[98] GEODH, "Developing geothermal district heating." [Online]. Available: http://geodh.eu/

[99] European Parliament and European Council, *Directive (EU) 2019/1161 of the European Parliament and of the Council of 20 June 2019 amending Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles (Text with EEA relevance.) PE/57/2019/REV/2*. 2019. Accessed: Jul. 05, 2021. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2019/1161/oj

[100] R. Bhandari, C. A. Trudewind, and P. Zapp, "Life cycle assessment of hydrogen production via electrolysis – a review," *J. Clean. Prod.*, vol. 85, pp. 151–163, Dec. 2014, doi: 10.1016/j.jclepro.2013.07.048.

[101] R. d'Amore-Domenech, Ó. Santiago, and T. J. Leo, "Multicriteria analysis of seawater electrolysis technologies for green hydrogen production at sea," *Renew. Sustain. Energy Rev.*, vol. 133, p. 110166, Nov. 2020, doi: 10.1016/j.rser.2020.110166.

[102] P. A. Pilavachi, S. D. Stephanidis, V. A. Pappas, and N. H. Afgan, "Multi-criteria evaluation of hydrogen and natural gas fuelled power plant technologies," *Appl. Therm. Eng.*, vol. 29, no. 11–12, pp. 2228–2234, Aug. 2009, doi: 10.1016/j.applthermaleng.2008.11.014.

[103] José Pablo Chaves *et al.*, "Identification of relevant market mechanisms for the procurement of flexibility needs and grid services - Deliverable: D5.1," *EUniversal Horiz. 2020 Proj.*, 2021, Accessed: Mar. 04, 2021. [Online]. Available: https://euniversal.eu/wp-content/uploads/2021/02/EUniversal_D5.1.pdf

[104] Bettina Kampman, Jaco Blommerde, and Maarten Afman, "The potential of energy citizens in the European Union," Delft, 2016. Accessed: Jun. 23, 2021. [Online]. Available: https://ce.nl/wp-content/uploads/2021/03/CE_Delft_3J00_Potential_energy_citizens_EU_final_1479221398.pdf

[105] Gianni Celli, Fabrizio Pilo, Simona Ruggeri, and Gian Giuseppe Soma, "Impact study on the utilisation of DER Flexibilities for DSO Network Management," in *Proceedings CIGRE Chengdu 2019 Symposium*, Chengdu (CINA): e-CIGRE, 2019. [Online]. Available: https://e-cigre.org/publication/SYMP_CHEN_2019-symposium-chengdu-2019

[106] Clara Gouveia *et al.*, "EUniversal Deliverable: D1.2 - Observatory of research and demonstration initiatives on future electricity grids and markets." EUniversal EU H2020 project. [Online]. Available: https://euniversal.eu/wp-content/uploads/2021/02/EUniversal_D1.2.pdf

[107] R. Haberfellner, O. de Weck, E. Fricke, and S. Vössner, *Systems Engineering: Fundamentals and Applications*. Springer, 2019.

[108] M. Tapia, P. Thier, and S. Gößling-Reisemann, "Building resilient cyber-physical power systems: An approach using vulnerability assessment and resilience management," *TATuP - Z. Für Tech. Theor. Prax.*, vol. 29, no. 1, Art. no. 1, Apr. 2020, doi: 10.14512/tatup.29.1.23.

[109] M. Uslar *et al.*, "Applying the Smart Grid Architecture Model for Designing and Validating System-of-Systems in the Power and Energy Domain: A European Perspective," *Energies*, vol. 12, no. 2, Art. no. 2, Jan. 2019, doi: 10.3390/en12020258.

[110] C. Süfke and C. Hermanns, "Scalable ICT-Structure for Smart Grid Solutions for Local Energy Communities," Jun. 2018, doi: 10.34890/266.

[111] S. Marksteiner, "Reasoning on Adopting OPC UA for an IoT-Enhanced Smart Energy System from a Security Perspective," in *2018 IEEE 20th Conference on Business Informatics (CBI)*, Jul. 2018, vol. 02, pp. 140–143. doi: 10.1109/CBI.2018.10060.

[112] S. Sučić, S. Rohjans, and W. Mahnke, "Semantic smart grid services: Enabling a standards-compliant Internet of energy platform with IEC 61850 and OPC UA," in *Eurocon 2013*, Jul. 2013, pp. 1375–1382. doi: 10.1109/EUROCON.2013.6625158.

[113] P. Elsner, B. Erlach, M. Fischedick, B. Lunz, and U. Sauer, "Flexibilitätskonzepte für die Stromversorgung 2050: Technologien, Szenarien, Systemzusammenhänge," 2016.

[114] acatech, "Zentrale und dezentrale Elemente im Energiesystem," Deutsche Akademie der Technikwissenschaften e.V., Stellungnahme, 2020.

[115] F. Pilo, G. Pisano, S. Ruggeri, and M. Troncia, "Data Analytics for Profiling Low-Voltage Customers with Smart Meter Readings," *Appl. Sci.*, vol. 11, no. 2, p. 500, Jan. 2021, doi: 10.3390/app11020500.

[116] T. Gómez, C. Mateo, Á. Sánchez, P. Frías, and R. Cossent, "Reference Network Models: A Computational Tool for Planning and Designing Large-Scale Smart Electricity Distribution Grids," in *High Performance Computing in Power and Energy Systems*, S. K. Khaitan and A. Gupta, Eds. Berlin, Heidelberg: Springer, 2013, pp. 247–279. doi: 10.1007/978-3-642-32683-7_9.

[117] C. Mateo *et al.*, "Building Large-Scale U.S. Synthetic Electric Distribution System Models," *IEEE Trans. Smart Grid*, vol. 11, no. 6, pp. 5301–5313, Nov. 2020, doi: 10.1109/TSG.2020.3001495.

[118] E. Aliyev, C. Morris, B. Elzarei, and E. Degasperi, "EUniversal-D.3.1-Flexibility-toolbox.pdf," 2020. Accessed: Dec. 28, 2020. [Online]. Available: https://euniversal.eu/wp-content/uploads/2020/12/EUniversal-D.3.1-Flexibility-toolbox.pdf

[119] A. Kollmann, V. Azarova, and I. Annex, "Asymmetric benefits of Smart Grids - IEA-ISGAN Annex 3 Discussion Paper," ISGAN - International Smart Grid Action Network, Vienna, 2017. [Online]. Available: https://www.iea-isgan.org/asymmetric-benefits-of-smart-grids/

[120] José Pablo Chaves Ávila, Matteo Troncia, Carlos Damas Silva, and Gwen Willeghems, "Overview of market designs for the procurement of system services by DSOs and TSOs - OneNet D3.1," OneNet H2020 Project, 2021.

[121] European Smart Grids Task Force Expert Group 3, "Final Report: Demand Side Flexibility Perceived barriers and proposed recommendations," Apr. 2019. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/eg3_final_report_demand_side_flexibility_2019.04.15.pdf

[122] Smart Energy Demand Coalition, "Explicit and Implicit Demand-Side Flexibility; Complementary Approaches for an Efficient Energy System, Position Paper," 2016.

[123] USEF, "Flexibility Value Chain, Update 2018. Main authors: Aliene van der Veen, Marten van der Laan, Hans de Heer, Elke Klaassen, and Willem van den Reek," 2018.

[124] Eurelectric, "A Bright Future for Europe. The value of electricity in decarboniz-ing the European Union," Eurelectric, Brussels-Belgium, 2017. Accessed: Jun. 30, 2021. [Online]. Available: https://www.eurelectric.org/media/1136/electrification_report_-_a_bright_future_for_europe-2017-030-0291-01-e.pdf

[125] M. Correa, T. Gòmez, and R. Cossent, "Local flexibility mechanisms for electricity distribution through regulatory sandboxes: international review and a proposal for Spain," presented at the 14th PowerTech Conference, Madrid, Spain, 2021.

[126] S. Allard, V. Debusschere, S. Mima, T. T. Quoc, N. Hadjsaid, and P. Criqui, "Considering distribution grids and local flexibilities in the prospective development of the European power system by 2050," *Appl. Energy*, vol. 270, p. 114958, Jul. 2020, doi: 10.1016/j.apenergy.2020.114958.

[127] G. Chicco, "Electricity market evolution in Europe," *Sci Bull Electr Eng Fac*, vol. 2, pp. 13–22, 2009.

[128] G. Rothwell and T. Gómez San Roman, *Electricity Economics: Regulation and Deregulation*. John Wiley & Sons, 2003. [Online]. Available: https://www.ebook.de/de/product/3604965/rothwell_gomez_san_rom_regulation_and_deregulation.html

[129] European Union, "Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC - Statements made with regard to decommissioning and waste management activities," *J. Eur. Union*, 2003.

[130] European Union, "Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC," *J. Eur. Union*, 2009.

[131] International Renewable Energy Agency (IRENA), "Innovation landscape brief: Co-operation between transmission and distribution system operators," *Int. Renew. Energy Agency Abu Dhabi*, 2020, [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jul/IRENA_TSO-DSO_co-operation_2020.pdf?la=en&hash=5D78444F4339DC130204A0F9A99A30753368AABC

[132] European Union, "Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU," *J. Eur. Union*, 2019.

[133] CEN-CENELEC-ETSI Smart Grid Coordination Group, "Smart Grid Reference Architecture," CEN-CENELEC-ETSI, 2012. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/xpert_group1_reference_architecture.pdf

[134] S. Oberthür and C. Dupont, *Decarbonization in the European Union: Internal Policies and External Strategies*. Springer, 2015.

[135] European Union, “Going climate-neutral by 2050: a strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy,” *Publ. Off. Eur. Union*, 2019, [Online]. Available: http://op.europa.eu/en/publication-detail/-/publication/92f6d5bc-76bc-11e9-9f05-01aa75ed71a1

[136] I. Abdelmotteleb, T. Gómez, and J. P. Chaves-Avila, “Benefits of PV inverter volt-var control on distribution network operation,” in *2017 IEEE Manchester PowerTech*, Jun. 2017, pp. 1–6. doi: 10.1109/PTC.2017.7981098.

[137] M. Birk, J. P. Chaves-Ávila, T. Gómez, and R. Tabors, “TSO/DSO Coordination in a context of distributed energy resource penetration,” p. 28, 2017.

[138] M. Troncia, J. P. C. Ávila, F. Pilo, and T. G. S. Román, “Remuneration mechanisms for investment in reactive power flexibility,” *Sustain. Energy Grids Netw.*, p. 100507, Jun. 2021, doi: 10.1016/j.segan.2021.100507.

[139] European Union, *Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (Text with EEA relevance.)*, vol. OJ L. 2019. Accessed: Dec. 26, 2020. [Online]. Available: http://data.europa.eu/eli/dir/2019/944/oj/eng

[140] IRENA, “Future role of distribution system operators – Innovation Landscape Brief.” International Renewable Energy Agency, Abu Dhabi, 2019.

[141] S. Ruester, S. Schwenen, C. Batlle, and I. Pérez-Arriaga, “From distribution networks to smart distribution systems: Rethinking the regulation of European electricity DSOs,” *Util. Policy*, vol. 31, pp. 229–237, Dec. 2014, doi: 10.1016/j.jup.2014.03.007.

[142] European Commission. Joint Research Centre., *Distribution system operators observatory 2020 :an in depth look on distribution grids in Europe.* LU: Publications Office, 2021. Accessed: Jun. 30, 2021. [Online]. Available: https://data.europa.eu/doi/10.2760/791730

[143] ISGAN - International Smart Grid Action Network, “Policy messages on Innovative Regulatory Approaches with Focus on Experimental Sandboxes to Enable Smart Grid Deployment,” 2019. [Online]. Available: https://www.iea-isgan.org/wp-content/uploads/2019/05/ISGAN-Policy-Messages-on-Sandboxes-to-the-Clean-Energy-Ministerial.pdf

[144] M. Wechsler, L. Perlman, and N. Gurung, “The State of Regulatory Sandboxes in Developing Countries,” *SSRN Electron. J.*, Jan. 2018, doi: 10.2139/ssrn.3285938.

[145] B. Knight and T. Mitchell, “The Sandbox Paradox: Balancing the Need to Facilitate Innovation with the Risk of Regulatory Privilege,” *SSRN Electron. J.*, Jan. 2020, doi: 10.2139/ssrn.3590711.

[146] Randolph Brazier *et al.*, “Smart Grid Key Performance Indicators: A DSO perspective.” CEDEC, E.DSO, Eurelectric, Geode, 2021. [Online]. Available: https://www.edsoforsmartgrids.eu/wp-content/uploads/20210315_SGI_Report_DSO_Only_final.pdf

[147] European Commission. Directorate General for Energy, “Clean energy for all Europeans,” *Publ. Off. Eur. Union*, 2019, doi: 10.2833/9937.

[148] G. Doorman *et al.*, *Capacity Mechanisms: Needs, Solutions Andstate of Affairs*. Paris: CIGRE, 2016. [Online]. Available: https://e-cigre.org/publication/647-capacity-mechanisms-needs-solutions-and-state-of-affairs

[149] D. Mills, L. Vlacic, and I. Lowe, “Improving electricity planning — Use of a multicriteria decision making model,” *Int. Trans. Oper. Res.*, vol. 3, no. 3, pp. 293–304, Jul. 1996, doi: 10.1016/S0969-6016(96)00023-8.

[150] G. Celli, N. Chowdhury, F. Pilo, G. G. Soma, M. Troncia, and I. M. Gianinoni, "Multi-Criteria Analysis for decision making applied to active distribution network planning," *Electr. Power Syst. Res.*, vol. 164, pp. 103–111, Nov. 2018, doi: 10.1016/j.epsr.2018.07.017.

[151] F. Ackerman and L. Heinzerling, "Pricing the Priceless: Cost-Benefit Analysis of Environmental Protection," *Univ. Pa. Law Rev.*, vol. 150, no. 5, p. 1553, May 2002, doi: 10.2307/3312947.

[152] ENTSO-E, "3rd ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects (Draft version 28 January 2020)," 2020. Accessed: Dec. 31, 2020. [Online]. Available: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/2020-01-28_3rd_CBA_Guidleine_Draft.pdf

[153] V. Giordano, I. Onyeji, G. Fulli, M. Sánchez Jiménez, and C. Filiou, *Guidelines for conducting a cost-benefit analysis of smart grid projects*. Luxembourg: Publications Office of the European Union, 2012. [Online]. Available: https://ec.europa.eu/jrc/en/publication/reference-reports/guidelines-conducting-cost-benefit-analysis-smart-grid-projects

[154] V. Giordano, I. Onyeji, G. Fulli, M. Sánchez Jiménez, and C. Filiou, *Guidelines for cost benefit analysis of smart metering deployment*. Luxembourg: Publications Office of the European Union, 2012. [Online]. Available: https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/guidelines-cost-benefit-analysis-smart-metering-deployment

[155] V. Giordano, S. Vitiello, and J. Vasiljevska, "Definition of an assessment framework for projects of common interest in the field of smart grids," JRC Science and policy reports, 2014. [Online]. Available: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC79445/ldna25828enn.pdf

[156] J. Vasiljevska and S. Gras, *Assessment framework for projects of common interest in the field of smart grids.* European Commission Publications Office, 2017. doi: 10.2760/37509.

[157] J. S. Dodgson, M. Spackman, A. Pearman, and L. D. Phillips, *Multi-criteria analysis: a manual*. Department for Communities and Local Government: London, 2009. [Online]. Available: http://eprints.lse.ac.uk/12761/1/Multi-criteria_Analysis.pdf

[158] K. Miettinen, "Introduction to Multiobjective Optimization: Noninteractive Approaches," in *Multiobjective Optimization*, Springer Berlin Heidelberg, 2008, pp. 1–26. doi: 10.1007/978-3-540-88908-3_1.

[159] European Union, *Regulation (EU) No 347/2013 of the European Parliament and of the Council of 17 April 2013 on guidelines for trans-European energy infrastructure and repealing Decision No 1364/2006/EC and amending Regulations (EC) No 713/2009, (EC) No 714/2009 and (EC) No 715/2009 Text with EEA relevance*, vol. 115. 2013. Accessed: Dec. 31, 2020. [Online]. Available: http://data.europa.eu/eli/reg/2013/347/oj/eng

[160] ENTSO-G, "2nd ENTSO-G CBA Methodology of Gas Infrustrucure Projects - Approved by European Commission." European Network of Transmission System Operators for Gas, Feb. 18, 2018.

[161] P. Beria, I. Maltese, and I. Mariotti, "Multicriteria versus Cost Benefit Analysis: a comparative perspective in the assessment of sustainable mobility," *Eur. Transp. Res. Rev.*, vol. 4, no. 3, pp. 137–152, Feb. 2012, doi: 10.1007/s12544-012-0074-9.

[162] J. A. Annema, N. Mouter, and J. Razaei, "Cost-benefit Analysis (CBA), or Multi-criteria Decision-making (MCDM) or Both: Politicians' Perspective in Transport Policy Appraisal," *Transp. Res. Procedia*, vol. 10, pp. 788–797, 2015, doi: 10.1016/j.trpro.2015.09.032.

[163] F. J. Sijtsma, "Project evaluation, sustainability and accountability: combining cost-benefit analysis (CBA) and multi-criteria analysis (MCA)," Stichting Ruimtelijke Economie Groningen, Rijksuniversiteit Groningen, 2006. Accessed: Dec. 31, 2020. [Online]. Available: http://hdl.handle.net/11370/89eb0f2f-35ef-4775-adc8-d54dc4f6bb83

[164] S. Leleur, N. Petersen, and M. Barfod, *The COSIMA Approach to Transport Decision Making: Combining Cost-benefit and Multi-criteria Analysis for Comprehensive Project Appraisal*. 2007.

[165] A. Gühnemann, J. J. Laird, and A. D. Pearman, "Combining cost-benefit and multi-criteria analysis to prioritise a national road infrastructure programme," *Transp. Policy*, vol. 23, pp. 15–24, Sep. 2012, doi: 10.1016/j.tranpol.2012.05.005.

[166] T. Kompas and S. Liu, "Comparing multi-criteria analysis and cost benefit analysis for biosecurity," p. 57.

[167] M. Clintworth, E. Boulougouris, and B. S. Lee, "Combining multicriteria decision analysis and cost–benefit analysis in the assessment of maritime projects financed by the European Investment Bank," *Marit. Econ. Logist.*, vol. 20, no. 1, pp. 29–47, Mar. 2018, doi: 10.1057/s41278-017-0072-x.

[168] K. Sjöstrand, A. Lindhe, T. Söderqvist, and L. Rosén, "Sustainability assessments of regional water supply interventions – Combining cost-benefit and multi-criteria decision analyses," *J. Environ. Manage.*, vol. 225, pp. 313–324, Nov. 2018, doi: 10.1016/j.jenvman.2018.07.077.

[169] M. Troncia, N. Chowdhury, F. Pilo, and I. M. Gianinoni, "A joint Multi Criteria - Cost Benefit Analysis for project selection on smart grids," in *2018 AEIT International Annual Conference*, Oct. 2018, pp. 1–6. doi: 10.23919/AEIT.2018.8577399.

[170] J. Hu, G. Yang, C. Ziras, and K. Kok, "Aggregator Operation in the Balancing Market Through Network-Constrained Transactive Energy," *IEEE Trans. Power Syst.*, vol. 34, no. 5, pp. 4071–4080, Sep. 2019, doi: 10.1109/TPWRS.2018.2874255.

[171] M. S. Nazir and I. A. Hiskens, "A Dynamical Systems Approach to Modeling and Analysis of Transactive Energy Coordination," *IEEE Trans. Power Syst.*, vol. 34, no. 5, pp. 4060–4070, Sep. 2019, doi: 10.1109/TPWRS.2018.2834913.

[172] J. Qiu, K. Meng, Y. Zheng, and Z. Y. Dong, "Optimal scheduling of distributed energy resources as a virtual power plant in a transactive energy framework," *IET Gener. Transm. Distrib.*, vol. 11, no. 13, pp. 3417–3427, Sep. 2017, doi: 10.1049/iet-gtd.2017.0268.

[173] K. A. Melendez, V. Subramanian, T. K. Das, and C. Kwon, "Empowering end-use consumers of electricity to aggregate for demand-side participation," *Appl. Energy*, vol. 248, pp. 372–382, Aug. 2019, doi: 10.1016/j.apenergy.2019.04.092.

[174] W. Liu, J. Zhan, and C. Y. Chung, "A novel transactive energy control mechanism for collaborative networked microgrids," *IEEE Trans. Power Syst.*, vol. 34, no. 3, pp. 2048–2060, May 2019, doi: 10.1109/TPWRS.2018.2881251.

[175] P. Siano, D. Sarno, L. Straccia, and A. T. Marrazzo, "A novel method for evaluating the impact of residential demand response in a real time distribution energy market," *J. Ambient Intell. Humaniz. Comput.*, vol. 7, no. 4, pp. 533–545, Aug. 2016, doi: 10.1007/s12652-015-0339-y.

[176] S. Burger, J. P. Chaves-Ávila, C. Batlle, and I. J. Pérez-Arriaga, "The Value of Aggregators in Electricity Systems," p. 29.

[177] IRENA, "Innovation landscape brief: Aggregators." International Renewable Energy Agency, Abu Dhabi, 2019.

[178] K. Zhou and S. Yang, "5.11 Smart Energy Management," in *Comprehensive Energy Systems*, I. Dincer, Ed. Oxford: Elsevier, 2018, pp. 423–456. doi: 10.1016/B978-0-12-809597-3.00525-3.

[179] S. De Clercq, D. Schwabeneder, C. Corinaldesi, and A. Fleischhacker, "Emerging aggregator business models in European electricity markets," in *Behind and Beyond the Meter*, Elsevier, 2020, pp. 285–303. doi: 10.1016/B978-0-12-819951-0.00014-1.

[180] A. Masood, J. Hu, A. Xin, A. R. Sayed, and G. Yang, “Transactive Energy for Aggregated Electric Vehicles to Reduce System Peak Load Considering Network Constraints,” *IEEE Access*, vol. 8, pp. 31519–31529, 2020, doi: 10.1109/ACCESS.2020.2973284.

[181] C. Long, J. Wu, Y. Zhou, and N. Jenkins, “Peer-to-peer energy sharing through a two-stage aggregated battery control in a community Microgrid,” *Appl. Energy*, vol. 226, pp. 261–276, Sep. 2018, doi: 10.1016/j.apenergy.2018.05.097.

[182] Ruben Verhaegen and Carlos Dierckxsens, “Existing business models for renewable energy aggregators,” BestRES H2020 project “Best practices and implementation of innovative business models for Renewable Energy aggregatorS,” 2016.

[183] Rafiek Versmissen, Eduardo Pallarés, and Joeri Posma, “CBA, regulatory analysis and business models - CBA Methodology and Results. InteGrid project D7.4.”

[184] S. Koch, “Chapter 2 - Assessment of Revenue Potentials of Ancillary Service Provision by Flexible Unit Portfolios,” in *Energy Storage for Smart Grids*, P. Du and N. Lu, Eds. Boston: Academic Press, 2015, pp. 35–66. doi: 10.1016/B978-0-12-410491-4.00002-6.