Horizon 2020
European Union funding
for Research & Innovation

EU-SysFlex Scenarios and Network Sensitivities

D2.2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773505.

PROGRAMME	H2020 COMPETITIVE LOW CARBON ENERGY 2017-2-SMART-GRIDS
GRANT AGREEMENT NUMBER	773505
PROJECT ACRONYM	EU-SysFlex
DOCUMENT	D2.2
TYPE (DISTRIBUTION LEVEL)	☒ Public ☐ Confidential ☐ Restricted
DUE DELIVERY DATE	31/10/2018
DATE OF DELIVERY	30/10/2018
STATUS AND VERSION	V1
NUMBER OF PAGES	91
Work Package / TASK RELATED	WP2/Task 2.2
Work Package / TASK RESPONSIBLE	Noel Cunniffe (EirGrid) / Sheila Nolan (EirGrid)
AUTHOR (S)	Sheila Nolan (EirGrid), Noel Cunniffe (EirGrid), Pádraig Daly (EirGrid), Caroline Bono (EDF), Marie-Ann Evans (EDF), Camille Cany (EDF), Anne Debregeas (EDF), Jussi Ikäheimo (VTT), Hannele Holttinen (VTT), Przemyslaw Kacprzak (PSE), Marek Duk (PSE), Tomasz Barlik (PSE), Wiebke Albers (Innogy), Anastasios Oulis Rousis (Imperial College).

DOCUMENT HISTORY

VERS	ISSUE DATE	CONTENT AND CHANGES
0.1	03/10/2018	First version
0.2	18/10/2018	Second version – Changes proposed through the internal review, reviewers: Marie-Ann Evans (EDF), Noel Cunniffe (EirGrid)
0.3	19/10/2018	Third version – For submission to the PMB, changes proposed through the internal review
1	30/10/2018	Final version – For submission to the European Commission, minor changes proposed through the review from the PMB

DOCUMENT APPROVERS

PARTNER	APPROVER
EirGrid	Noel Cunniffe (Work Package Leader)
EDF	Marie-Ann Evans (Technical Manager)
EirGrid, EDF, SONI, VITO, innogy, Elering, EDP, EURACTIV, Zabala	EU-SysFlex Project Management Board
EirGrid	John Lowry (Project Coordinator)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
DC	Direct Current
DSO	Distribution System Operator
EED	Energy Efficiency Directive
EHV	Extra High Voltage
EPBD	Energy Performance of Buildings Directive
ENTSO-E	European Network of Transmission System Operators for Electricity
ET	Energy Transition: The first EU-SysFlex Scenario
EU	European Union
EU-SysFlex	Pan-European System with an efficient coordinated use of flexibilities for the integration of a large share of Renewable Energy Sources
GHG	Greenhouse Gas
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
MVA	Mega Volt Ampere
MVAr	Mega Volt Ampere Reactive
NREAP	National Renewable Energy Action Plan
OCGT	Open Cycle Gas Turbine
PCI	Project of Common Interest
PHES	Pumped Hydro Energy Storage
POR	Primary Operating Reserve
RA	Renewable Ambition: The second EU-SysFlex Scenario
RES	Renewable Energy Sources
RES-E	Electricity from Renewable Energy Sources
SO	System Operator
SONI	System Operator Northern Ireland
SOR	Secondary Operating Reserve
TER	Total Energy Requirement
TOR	Tertiary Operating Reserve
TSO	Transmission System Operator
TYNDP	ENTSO-E’s Ten Year Network Development Plan
VRE	Variable Renewable Energy
WP	Work Package

EXECUTIVE SUMMARY

The EU-SysFlex project aims to identify large scale deployment of flexible solutions for a European power system with a high share of Renewable Energy Sources (RES). These solutions can include technical options, system services and market designs. The project results will contribute to enhanced system flexibility, coordinating the use of both existing and new technologies. Work Package (WP) 2 is the starting point of the project, as its goal is to evaluate the scarcities arising in the future system. Task 2.2 provides the initial assumptions made to meet the EU targets for the development of renewable sources in the European power system. These assumptions, presented as scenarios for the European power system are crucial to the EU-SysFlex project as they will feed into the models and simulations of the following WP2 tasks.

This report outlines the development process for scenarios and network sensitivities which will be used in the technical and market modelling analysis for the EU-SysFlex project. The outcome of this work is a set of coherent and transparent scenarios for the European power system, which are consistent with the aims and objectives of the EU-SysFlex project, and a number of network sensitivities which examine various sub-networks of the European power system in greater detail. The scenarios chosen for the EU-SysFlex project are a crucial starting point for the technical and market modelling analysis which is central to the project.

In developing scenarios for the EU-SysFlex project, two categories of scenarios were defined:

Core Scenarios – These are the central scenarios which will define the installed generation capacities by fuel type, demand, interconnection and storage portfolios to be used. These scenarios will be used to produce total annual energy demand as well as total annual energy production by source and fuel type. These scenarios will be used throughout the project for technical and production cost simulations on a European basis.

Network Sensitivities – These are sensitivities which examine various parts of the European network and will vary the capacities and locations of demand, generation, interconnection or storage in order to examine various scenarios in specific countries of the European power system. These sensitivities will be used to assess more specific technical scarcities in certain parts of the European system.

An initial investigation phase of the EU-SysFlex scenario development took place with a review of European scenario literature, starting in November 2017 to meet the February 2018 Milestone of the EU-SysFlex project, ‘MS1 – Agreement on Core Modelling Scenarios’. This literature review formed the starting point for the EU-SysFlex Scenarios. The review explored using data from the European Commission’s EU Reference Scenario 2016 and EUCO Policy Scenarios, and ENTSO-E Ten Year Network Development Plan (TYNDP) 2018 Scenarios. In addition, the e-highways2050 scenarios and EDF’s 60% RES-E (Electricity from Renewable Energy Sources) pan-European scenario were also investigated.

Following this assessment, it was determined that the EU Reference Scenarios 2016 would form the basis for the two core scenarios chosen for the EU-SysFlex project. The EU Reference Scenarios 2016 met the criteria defined for the EU-SysFlex scenario selection in that:

- They are consistent with the goals of the EU-SysFlex project (i.e. they have at least 50% RES-E for the European power system);
- They have a publicly available and complete dataset for each of the scenarios with individual EU28 country breakdowns;
- They incorporate the targets, policies and directives of the European Union;
- They are recently developed scenarios as they were published in 2016; and
- By using two scenario years of the EU Reference Scenarios 2016, horizon 2030 and horizon 2050 for a higher RES target, there is a direct and coherent relationship between the two Core Scenarios to allow for easy comparisons – with one of the scenarios being more ambitious than the other in terms of the scale of the renewables energy production.

The two chosen scenarios are based on the generation and demand portfolios for the European Commission's EU Reference Scenario 2016 for 2030 and 2050 respectively using various 2030 European network models for EU-SysFlex simulations. Information from the EU Reference Scenarios 2016 was supplemented with additional information from other sources for countries outside of the EU, and for obtaining information on profiles for Electric Vehicles and Heat Pumps. This included information from the ENTSO-E TYNDP 2018 scenarios for Norway and Switzerland. For the purposes of the EU-SysFlex project, the two scenarios will be known as the **Energy Transition** scenario, which is based on the EU Reference Scenario 2016's demand and generation portfolio for 2030, and the **Renewable Ambition** scenario, which is based on the EU Reference Scenarios 2016's demand and generation portfolio for 2050.

The **Energy Transition** Scenario has a percentage of electricity from renewable energy sources (RES-E) with respect to overall demand of 52%, while the **Renewable Ambition** Scenario has a RES-E percentage of 66%. These RES-E figures are consistent with the goal of the EU-SysFlex scenarios in examining the European power system at very high levels of renewable energy. The fact that two different time horizon portfolios from the EU Reference Scenarios 2016 are used for different ambition levels in the EU-SysFlex core scenarios provides a distinct advantage in having two linked scenarios for the entire European system, and the sub-networks and power systems chosen for additional analysis. These core scenarios and network sensitivities will be used throughout all aspects of the EU-SysFlex project. The scenarios enable consistency across all modelling tasks in various EU-SysFlex Work Packages which will increase the ease of comparing different analysis across the project.

In addition to the percentage of RES-E in the two core scenarios, the percentage of variable non-synchronous renewable resources is of particular interest to the EU-SysFlex project. As highlighted in the EU-SysFlex D2.1 – State-of-the-Art Literature Review of System Scarcities at High Levels of Renewables, the challenges of integrating high levels of renewable generation are primarily seen at times of high non-synchronous generation penetration.

Therefore, within the two core scenarios, the hours which have the highest levels of non-synchronous generation will be examined in detail through technical simulations to understand future system scarcities.

Table 1 provides a summary of the renewable generation production, electricity demand and RES-E levels seen for each European country in the two EU-SysFlex scenarios. Table 2 provides a summary of the carbon-free generation and non-synchronous variable renewable generation for each of the EU member states considered in the EU-SysFlex scenarios.

TABLE 1: PERCENTAGES OF RENEWABLE ENERGY PRODUCTION IN THE ENERGY TRANSITION AND RENEWABLE AMBITION SCENARIOS AS A PERCENTAGE OF DEMAND

	Energy Transition			Renewable Ambition		
Country	**RES production (TWh$_e$)**	**Demand (TWh$_e$)**	**%RES**	**RES production (TWh$_e$)**	**Demand (TWh$_e$)**	**%RES**
AT	62	73	85%	73	83	88%
BE	29	89	32%	41	108	37%
CH	45	61	74%	74	56	132%
CZ	9	66	14%	16	79	21%
DE	267	559	48%	385	580	66%
DK	29	36	80%	35	44	80%
ES	163	257	63%	282	291	97%
FI	43	84	51%	50	96	52%
FR	211	469	45%	362	548	66%
HU	3	39	8%	9	47	19%
IE	14	28	48%	21	34	63%
IT	148	314	47%	273	395	69%
LU	1	8	12%	2	12	14%
NL	50	116	43%	67	133	50%
NO	155	117	132%	160	110	145%
PL	40	168	24%	71	202	35%
PT	42	48	88%	50	51	98%
SE	113	144	78%	133	166	80%
SK	7	31	21%	10	34	31%
UK	176	356	49%	201	438	46%
Total	**1 607**	**3 063**	**52%**	**2 315**	**3 507**	**66%**

TABLE 2: CHARACTERISTICS OF THE EU-SYSFLEX SCENARIOS FOR THE 28 EU MEMBER STATES, SWITZERLAND AND NORWAY, FOR CARBON-FREE ELECTRICITY AND VARIABLE NON-SYNCHRONOUS RENEWABLE ENERGY (VRE) AS A PERCENTAGE OF ELECTRICITY PRODUCTION

	Energy Transition				Renewable Ambition			
Country	% carbon - free	% VRE	VRE of which		% carbon - free	% VRE	VRE of which	
			% Wind	% Solar			% Wind	% Solar
EU-28	**65**	**24**	**72**	**28**	**73**	**35**	**70**	**30**
AT	78	17	75	25	81	23	75	25
BE	40	32	83	17	41	33	84	16
BG	57	18	63	37	70	23	57	43
CH	94	13	26	74	100	18	27	73
CY	29	26	32	68	41	38	33	67
CZ	43	4	28	72	70	5	38	62
DE	44	31	68	32	60	43	70	30
DK	81	58	96	4	80	58	97	3
EE	21	11	100	0	67	42	100	0
ES	77	42	60	40	86	71	54	46
FI	77	8	100	0	91	8	100	0
FR	98	20	67	33	94	38	69	31
GR	57	46	63	37	78	66	58	42
HR	64	16	56	44	73	31	46	54
HU	90	2	90	10	77	9	85	15
IE	42	36	100	0	59	49	100	0
IT	46	21	49	51	65	36	41	59
LV	61	9	100	0	70	19	100	0
LT	81	6	93	7	82	14	97	3
LU	22	14	81	19	18	13	87	13
MT	13	13	-	100	22	20	13	87
NL	40	24	85	15	43	29	88	12
NO	97	10	100	-	99	12	96	4
PL	20	11	100	0	57	18	99	1
PT	87	41	79	21	96	52	71	29
RO	76	21	83	17	75	25	74	26
SE	93	13	100	0	94	14	100	0
SI	67	6	29	71	87	6	31	69
SK	94	2	4	96	84	4	23	77
UK	71	26	91	9	70	28	93	7

In addition to the **Energy Transition** and **Renewable Ambition** scenarios, various Network Sensitivities have been developed which seek to stress particular parts of the European network in order to examine further technical scarcities in greater detail. These Network Sensitivities are used to investigate more onerous or more ambitious generation and demand portfolios for specific areas and countries. The Network Sensitivities are focused on the areas of the European power system which will undergo increased analysis and simulations. Therefore, the areas which were primarily chosen for Network Sensitivities are the Ireland and Northern Ireland power system and a sub-network of the Continental European power system centred on the Poland network. Additionally, a further sensitivity for the Nordic system has been developed.

A summary of the scenarios and Network Sensitivities considered by all partners for further analysis is given in Table 3 below.

TABLE 3: SUMMARY OF THE SCENARIOS AND NETWORKS SENSITIVITIES DEVELOPED FOR THE EU-SYSFLEX PROJECT

Partner	System considered	Core Scenarios		Network Sensitivities		
EDF	Continental system	Energy Transition	Renewable Ambition	-	-	-
VTT	Nordic system	Energy Transition	Renewable Ambition	High Solar	-	-
PSE	Poland and neighbours	Energy Transition	Renewable Ambition	Going Green	Distributed Renewables	-
EirGrid & SONI	Ireland and Northern Ireland	Energy Transition	Renewable Ambition	Steady Evolution	Consumer Action	Low Carbon Living

The two core scenarios, **Energy Transition** and **Renewable Ambition**, and the various Network Sensitivities presented within this report will be used throughout the EU-SysFlex project.

The Core Scenarios and Network Sensitivities were developed using Unit Commitment software, which seeks to optimally schedule the generation of both thermal and hydro generation plants to meet system net demand (taking account of renewable generation and interconnectors) and indicates the number of hours of unserved energy in the system. The initial data set is adjusted iteratively to obtain thermal energy targets as close as possible to the annual targets of the EU Reference Scenarios as well as a number of unserved energy hours that meet a criterion of 3 hours of unserved energy on average for all European countries. This iterative process requires a lot of fine-tuning to deviate only marginally from the initial values from the EU Reference scenarios at horizon 2030 and 2050 in order to develop the **Energy Transition** and **Renewable Ambition scenarios**.

The total annual power production by primary energy resource for **Energy Transition** and **Renewable Ambition** is obtained from averaging the hourly production for each country by primary energy resource over 165 separate year-long simulations. Each of these simulations represents a year with different climatic conditions and generator outages. The model includes technical generator constraints as well as locational reserve constraints. There is excellent alignment between the energy production values as quoted in the EU References Scenarios and the two EU-SysFlex scenarios, **Energy Transition** and **Renewable Ambition**.

The output of this detailed modelling of the European power system is production schedules at an hourly resolution for a large range of climate years. Similarly, models have been developed for the Network Sensitivities for the various sub-networks of the European power system. This will allow the EU-SysFlex project to carry out state-of-the-art technical and economic studies of a system with a large amount of variable renewables, and make key contributions to the final flexibility roadmap of the EU-SysFlex project.

The dispatches from these models will be used in co-ordination with the technical models developed in Task 2.3. This will form the starting point for the technical simulations which will identify the future system scarcities of the European power system within Task 2.4. These scenarios will also be used in Task 2.5 to enable a valuation of future System Services to help solve the scarcities found within Task 2.4.

In addition to their use in WP2, the Core Scenarios and Network Sensitives will also be used in other Work Packages of the EU-SysFlex project. This includes Work Package 3, which will define new System Services and market designs for the future European power system, and Work Package 10 which will outline a roadmap for adapting the learnings of the entire EU-SysFlex project to enable the European power system to reach ambitious levels of renewable generation. As demonstrated, the Core Scenarios and Network Sensitivities documented in this report are central to the EU-SysFlex project.

1. INTRODUCTION

The EU-SysFlex project seeks to enable the European power system to utilise efficient, coordinated flexibilities in order to integrate high levels of renewable energy sources. One of the primary goals of the project is to examine the European power system with at least 50% of electricity coming from renewable energy sources (RES-E).

In order to reach at least 50% RES-E on a European scale, it will be necessary to integrate increasingly high levels of variable non-synchronous renewable technologies such as wind and solar. Transitioning from power systems which have traditionally been dominated by large synchronous generating units to systems with high levels of variable non-synchronous renewable technologies has been shown to result in challenges for operating power systems safely and reliably. This is due to the non-synchronous nature of these technologies as well as the variable and uncertain nature of the underlying resources. The integration of non-synchronous renewable generation results in the displacement of synchronous generators. This can consequently lead to technical scarcities in power systems as the new technologies do not replicate all of the traditional resilience functions of synchronous generators which they are replacing. The displacement of the synchronous generators also leads to brand new technical scarcities which have never been seen before. Addressing these challenges is at the core of the EU-SysFlex project.

In this regard, Work Package (WP) 2 forms a crucial starting point for the EU-SysFlex project. WP2 will perform detailed technical power system simulations in order to identify the technical scarcities of the European power system with high levels of renewable generation as well as high levels of electrification. Interactions between WP2 and the other WPs in the project can be seen in Figure 1.

The first deliverable of WP2 was completed as part of Task 2.1 - D2.1 - State-of-the-Art Literature Review of System Scarcities at High Levels of Renewable Generation (EU-SysFlex, 2018). Task 2.2 and this report, Deliverable 2.2, aim to define a set of pragmatic and ambitious scenarios for renewable generation deployment in Europe. The scenario development process was mindful of the findings from Deliverable 2.1 and the likely technical scarcities that the project seeks to explore in detail. The scenarios will be utilised not only within WP2 but also throughout the entire EU-SysFlex project and are central to the project. This ensures consistency in the analysis that is performed across the various WPs in the project.

In parallel to the development of these scenarios, Task 2.3 seeks to develop detailed models of the power system. These models will be utilised in Task 2.4, in conjunction with the scenarios, to perform detailed studies. The studies will encompass several geographical areas with different characteristics. This includes a Continental European model encompassing 20 countries, which will focus primarily on frequency stability, and further subsystems which will be used for more detailed analysis. These subsystems are the Nordic power system, the Ireland and Northern Ireland power system, and a sub-network of the Continental European system focussing on Poland and the surrounding countries. The aim of these simulations is to evaluate a range of technical scarcities.

The technical scarcities identified in WP2 are central to the EU-SysFlex project as they will feed into WP3 which will develop innovative system services and market and regulatory options to address them.

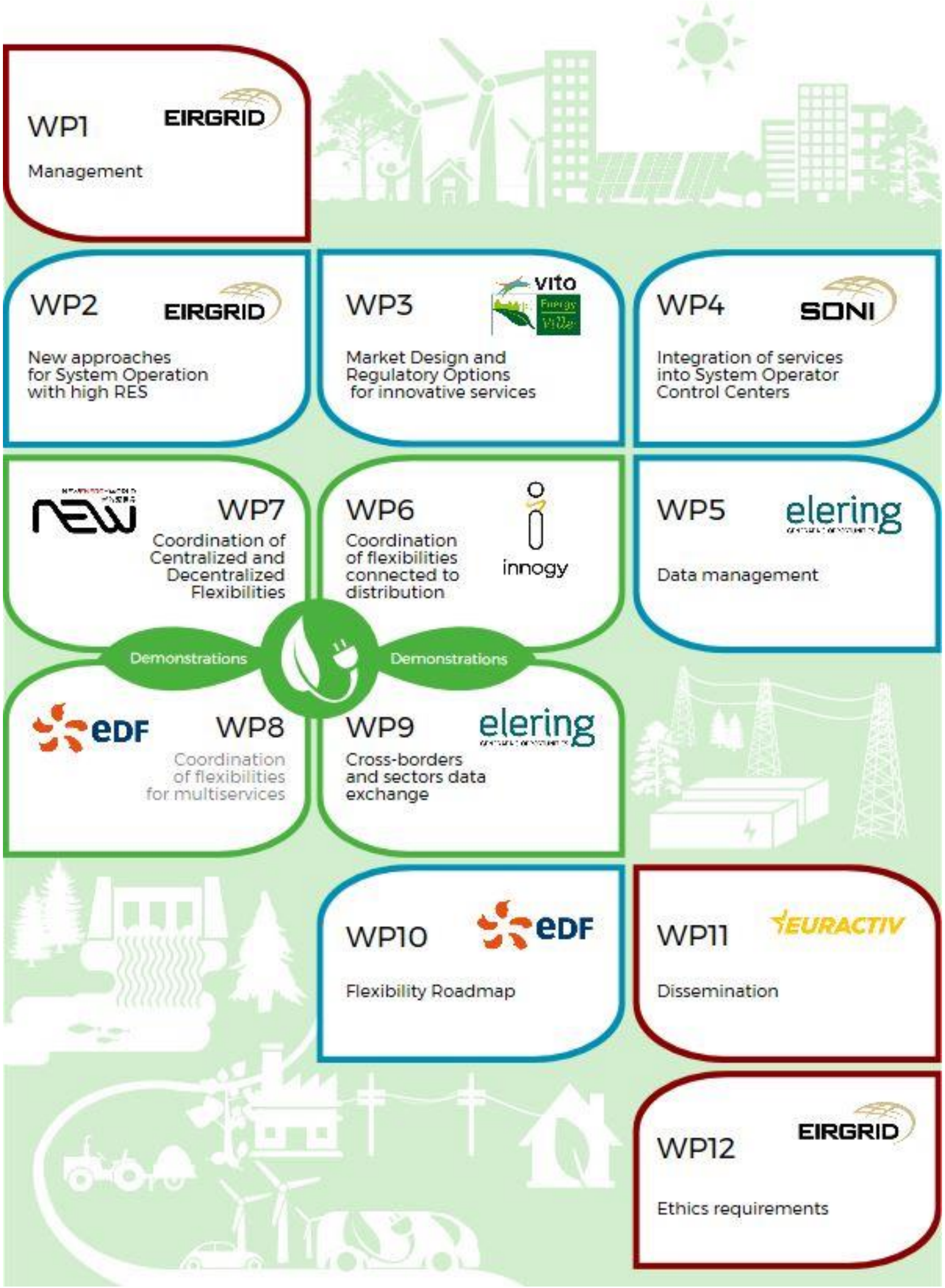


FIGURE 1: EU-SYSFLEX WORK PLAN

Concurrent to the technical studies in Task 2.4, production cost modelling, based on the scenarios documented in this report, will be performed in Task 2.5 for both the Continental European power system and the Ireland and Northern Ireland power system. These modelling studies will assess potential revenues for new technologies as well as identify financial gaps in the energy market. These gaps would need to be filled by new or increased revenue streams from system services in order to create sufficient investment signals for new technologies to be realised.

The final task in WP2, Task 2.6, will seek to incorporate the findings from other WPs in the EU-SysFlex project and incorporate proposed solutions to the scarcities identified based on the learnings from the project.

The power system assumptions utilised in WP2 for the technical simulations and production cost modelling, and the assumptions in WP3 for advanced electricity market modelling studies will be based on the EU-SysFlex scenarios. The scenarios chosen for the EU-SysFlex project are a crucial starting point for the technical and market modelling analysis which is central to the project.

2. METHODOLOGY FOR DEFINING EU-SYSFLEX SCENARIOS

2.1 OVERVIEW OF SCENARIO PLANNING

One of the most fundamental parts of planning the development of power system is forecasting how electricity generation and consumption will change over time, so as to determine which investments are needed to ensure a system with the safety and reliability that people have come to expect. It can also be the most difficult part of the process. There are a lot of different factors that effect changes in electricity generation and consumption. These factors include economic performance, population growth, government policies, technology developments and changes in consumer behaviour and attitudes. As a result, planning for our energy future can be a complex task. Scenario planning is a method of planning for an uncertain future.

Many Transmission System Operators (TSOs) and Distribution System Operators (DSOs), as well as other stakeholders, now engage in scenario development and planning as part of their planning process for the future of the power system. The extent of the detail that is incorporated in the scenario development process varies across stakeholders and varies depending on the need for the scenarios.

In developing scenarios for the EU-SysFlex project, two categories of scenarios were defined:

Core Scenarios – These are the central scenarios which will define the installed generation capacities by fuel type, demand, interconnection and storage portfolios to be used. These scenarios will be used to produce total annual energy demand as well as total annual energy production by source and fuel type. These scenarios will be used throughout the project for technical and production cost simulations on a European basis.

Network Sensitivities – These are sensitivities which examine various parts of the European network and will vary the capacities and locations of demand, generation, interconnection or storage in order to examine various scenarios in specific countries of the European power system. These sensitivities will be used to assess more specific technical scarcities in certain parts of the European system.

An initial investigation phase of the EU-SysFlex scenario development took place with a review of European scenario literature, starting in November 2017 to meet the February 2018 Milestone of the EU-SysFlex project, ‘MS1 – Agreement on Core Modelling Scenarios’. This literature review formed the starting point for the EU-SysFlex Scenarios. The review explored using data from the European Commission’s EU Reference Scenario 2016 (European Commission, 2016) and EUCO Policy Scenarios (E3MLab & IIASA, 2016), and ENTSO-E Ten Year Network Development Plan (TYNDP) 2018 Scenarios (ENTSO-E, 2018). In addition, e-highways 2050 scenarios (e-Highway2050, 2013) and EDF’s 60% RES-E Continental European scenario (Burtin & Silva, 2015) were also investigated. Brief overviews of the reviewed scenarios are provided below.

2.1.1 EU REFERENCE SCENARIOS 2016

The EU Reference Scenarios 2016 are utilised by the European Commission as a vital tool for analysis in the areas of energy, transport and climate change. It is intended that the EU Reference Scenarios act as a benchmark of current policy and market trends and they aim to assist policy-makers perform long-term economic, energy and climate analysis (European Commission, 2016). The scenarios set out a trajectory from 2020 to 2050 and are based on the current policy framework, with defined scenarios every five years. The scenarios integrate all of the European policies and directives which have been adopted at EU level and in Member States by December 2014, and meet the 2020 RES-E targets set by the European Commission. The scenarios account for the successful implementation of the EU Emissions Trading Scheme (ETS) and see significant CO_2 reduction over the projected scenario years. A suite of interlinked models were utilised to produce projections for the energy sector and the agricultural and forestry sector for each of the EU-28 countries. The scenarios include CO_2 emission assumptions and outline projections for generation, demand, storage and interconnection portfolios.

2.1.2 EUROPEAN COMMISSION (EUCO) POLICY SCENARIOS

The European Commission (EUCO) Policy Scenarios build upon the aforementioned EU Reference Scenarios and all of the EUCO Policy Scenarios are built from the same starting point; the EU Reference Scenario 2016. Additional targets and policy assumption are then incorporated to further enhance the projections. These extra assumptions include an increase in the EU ETS price and additional RES and energy efficiency policies. As with the EU Reference Scenarios, the EUCO Policy Scenarios provide projections for all EU-28 countries. However, the EUCO scenarios provide projections only up to the year 2030. Several sensitivities are developed relating to varying levels of energy efficiency and renewable energy increases.

2.1.3 ENTSO-E TEN YEAR NETWORK DEVELOPMENT PLAN (TYNDP) SCENARIOS 2018

The ENTSO-E Ten Year Network Development Plan (TYNDP) 2018 uses different scenarios at different time horizons from 2020 up to 2040 in order to give a view on what additional grid infrastructure is needed and where. Each scenario provides a storyline for different possible futures which aim to achieve Europe's decarbonisation objectives. These scenarios are then used in transmission network analysis to identify areas of the network which will require further investment. These scenarios are used to assess Projects of Common Interest (PCI) between different EU member states. The outputs of TYNDP 2018 show that even with decentralised generation, demand response, storage and energy efficiency playing an increasing role, an extension of the current grid is needed to allow the shift of large quantities of renewables to the main consumption centres.

The TYNDP 2018 scenarios consist of four scenarios for 2030 and 2040 which are summarised in the TYNDP 2018 Scenario Report as follows:

- **Distributed generation (2030 and 2040)** - Prosumers at the centre – small-scale generation, batteries and fuel switching society engaged and empowered.
- **Sustainable Transition (2030 and 2040)** - Targets reached through national regulation, emission trading schemes and subsidies, maximising the use of existing infrastructure.
- **The EUCO Scenario (2030)** – An external scenario, EUCO 30, which was developed by the European Commission. This is documented in section 2.1.2 above.
- **Global Climate Action (2040)** - Full speed global decarbonisation, large-scale renewables development in both electricity and gas sectors.

Further information on these scenarios can be found in the TYNDP Scenarios 2018 report (ENTSO-E, 2018).

2.1.4 E-HIGHWAY2050 SCENARIOS

The e-Highway2050 project aims to develop a methodology to support network planning of the Continental European transmission network (e-Highway2050, 2013). Under pinning the e-Highways project is the EU energy policy. The project adopted a top down approach for development of the e-Highway2050 scenarios. This approach, as illustrated in Figure 2, included the following steps:

- Identification of relevant uncontrollable uncertainties (e.g. costs of technology, economic growth) and controllable options (e.g. subsidies/support schemes);
- Combining uncertainties into a ‘Set of Futures’ and Options into ’Set of Strategies’;
- Combining coherent Futures and Strategies into coherent Scenarios; and
- Reducing the number of Scenarios by combining Scenarios that have similar effect.

In the e-Highway2050 report, five futures were developed. These were ‘Green Globe’, ‘Green EU’, ‘EU-Market’, ‘Big is beautiful’ and ‘Small things matter’. In addition, 6 Strategies were described. These strategies include ‘Market led’, ‘Large scale RES solutions’, ‘Local solutions’, ‘100% RES’, ‘Carbon-free CSS and nuclear’ and ‘No nuclear’. Combining these five futures and six strategies produces 30 scenarios. Eliminating duplications, the e-Highways 2050 project finally produced 5 scenarios:

- **Large scale RES & no emission** – this scenario is characterised by deployment of large scale RES technologies, e.g. large scale off shore wind parks.
- **100% RES** – in this scenario Europe’s energy system is entirely based on renewable energy – 100 % Greenhouse gas (GHG) reduction, both large scale and small scale are used.
- **Big & Market** – Europe relies mainly on a market based strategy to achieve GHG reduction, moreover in this scenario, there is a special interest on large scale centralized solutions, especially for RES deployment and storage.

- **Large fossil fuel with Carbon Capture and Storage (CCS) and nuclear** – Europe is mainly following a non-RES strategy to reach GHG reduction target and this is achieved though nuclear generation and carbon capture and storage.
- **Small and local** – Europe is following GHG reduction mostly via small-scale/local solutions.

In each scenario Europe is fully committed to meeting 80-95% GHG reduction, except in the 100% RES scenario, where a 100% reduction in GHG emissions is envisioned. Further information on these scenarios can be found in the e-Highway2050 publications (e-Highway2050, 2013).

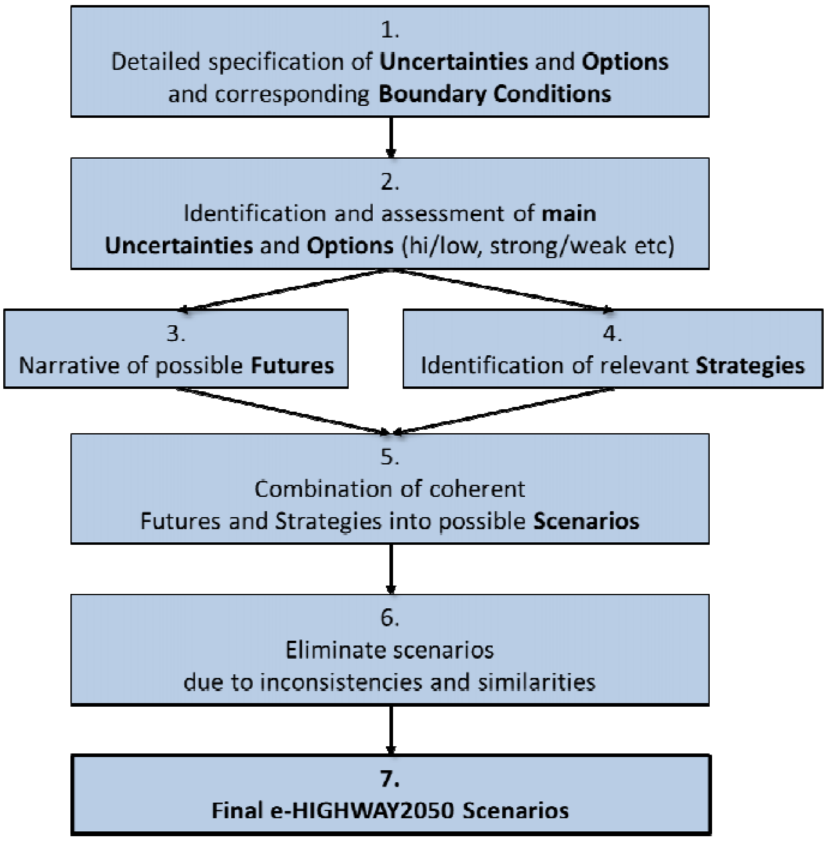
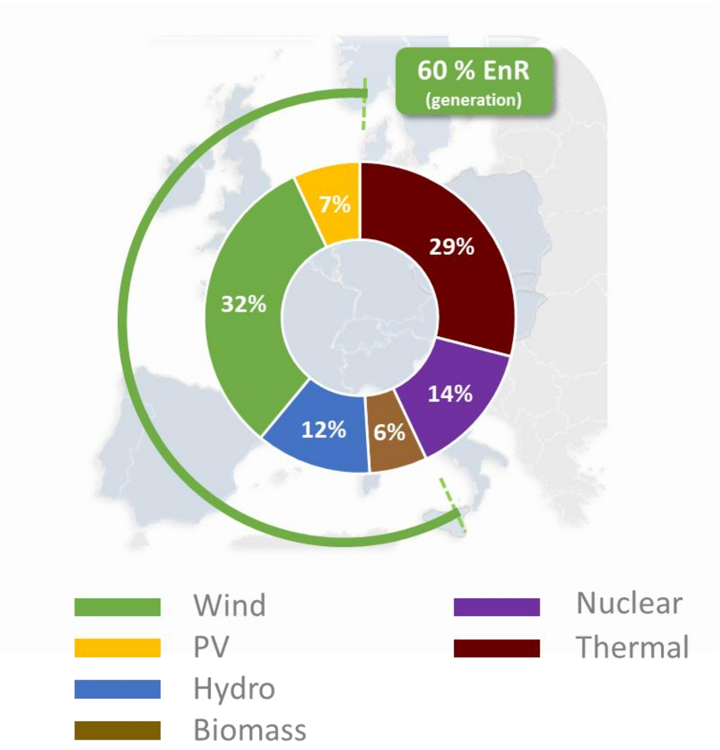


FIGURE 2: E-HIGHWAY2050 SCENARIO DEVELOPMENT PROCESS (E-HIGHWAY2050, 2013)

2.1.5 60% RES-E

EDF developed a scenario for the European power system with 60% RES-E in 2030 to look at the technical and economic implication of a massive deployment of RES-E at European level (Burtin & Silva, 2015). The scenario was developed using the targets for the 2030 Hi-RES scenario of the 2050 Energy Roadmap from European Union (European Commission, 2012). The share of RES-E reaches 60%, which includes a VRE share consisting of wind and solar, of 40%. Figure 3 shows the installed capacity of RES-E in the scenario. Overall, 705 GW of variable renewable energies (wind and solar) are installed. Using the aggregated European targets in the scenario, EDF built a dataset that is on an hourly basis for an entire year for each country and for approximately 30 different occurrences of climate years. Installed RES capacities were placed in the locations with the best capacity factor potentials and RES generation was computed using a bottom-up approach. Therefore, this dataset keeps the spatial and temporal correlation across the European system. The assumptions and results for this study were published in (Burtin & Silva, 2015).



High RES 2030	GW	Load factor (h/yr)
Solar (PV)	220	1100
Onshore wind	280	1900
Offshore wind	205	3200
Hydro	120	3800

FIGURE 3: INSTALLED RES-E CAPACITY FOR THE 60% RES-E SCENARIO (BURTIN & SILVA, 2015)

2.2 AIMS AND OBJECTIVES OF THE EU-SYSFLEX SCENARIOS

The scenarios developed as part of Task 2.2, must adhere to one key criterion for the EU-SysFlex project – a European power system with at least 50% electricity from renewable energy sources. The Core Scenarios and Network Sensitivities will be used throughout all aspects of the EU-SysFlex project. The scenarios enable consistency across all modelling tasks in various EU-SysFlex WPs which will increase the ease of comparing different analysis across the project.

As can be seen from Figure 4 and Figure 5, the Core Scenarios, which are implemented in the EDF Continental model, are the starting point for the technical simulations within WP2. In addition, the installed capacity projections, and other assumptions, from the Core Scenarios will be fundamental to the simulations that will be undertaken in WP3. As can be seen in Figure 4, there are numerous diverse models developed as part of Task 2.3 which are documented in the EU-SysFlex D2.3 report (EU-SysFlex, 2018). The models are connected through the use of the installed generation and demand portfolios of the Core Scenarios. Consequently, it is important that these scenarios are robust and pragmatic, but also ambitious and optimistic in terms of renewable energy development assumptions.

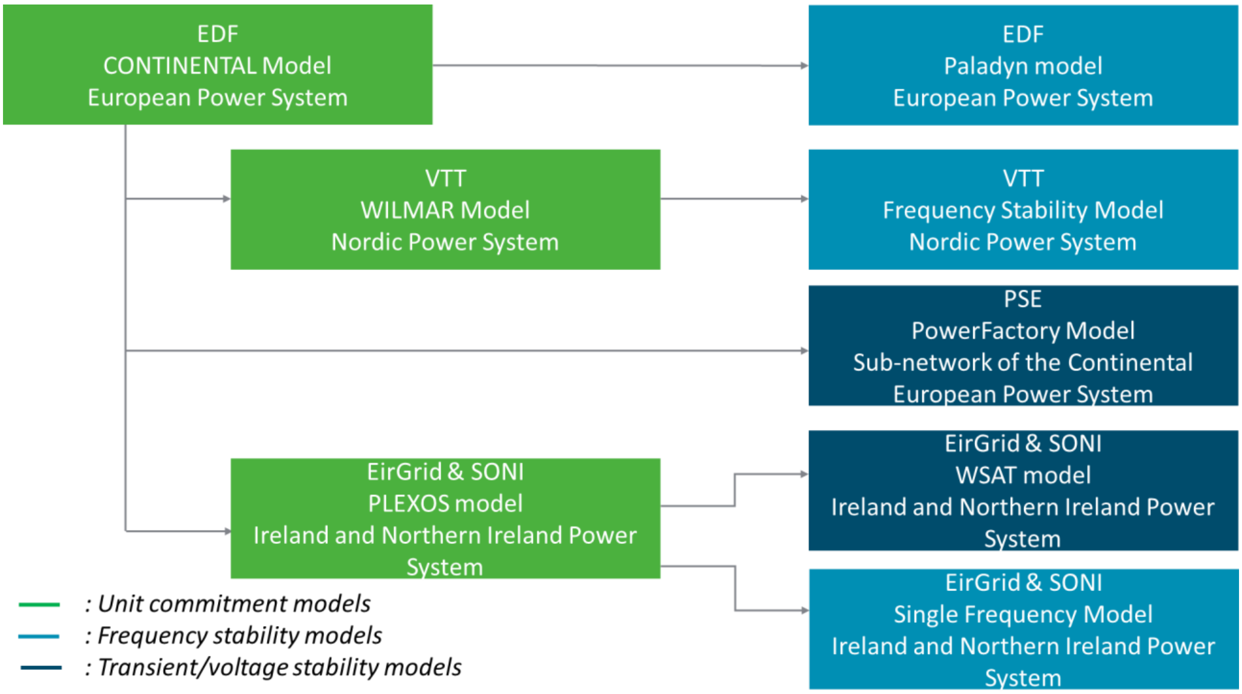


FIGURE 4: OVERVIEW OF THE STUDIES WORKFLOW FOR WP2 RELYING ON THE CORE SCENARIOS

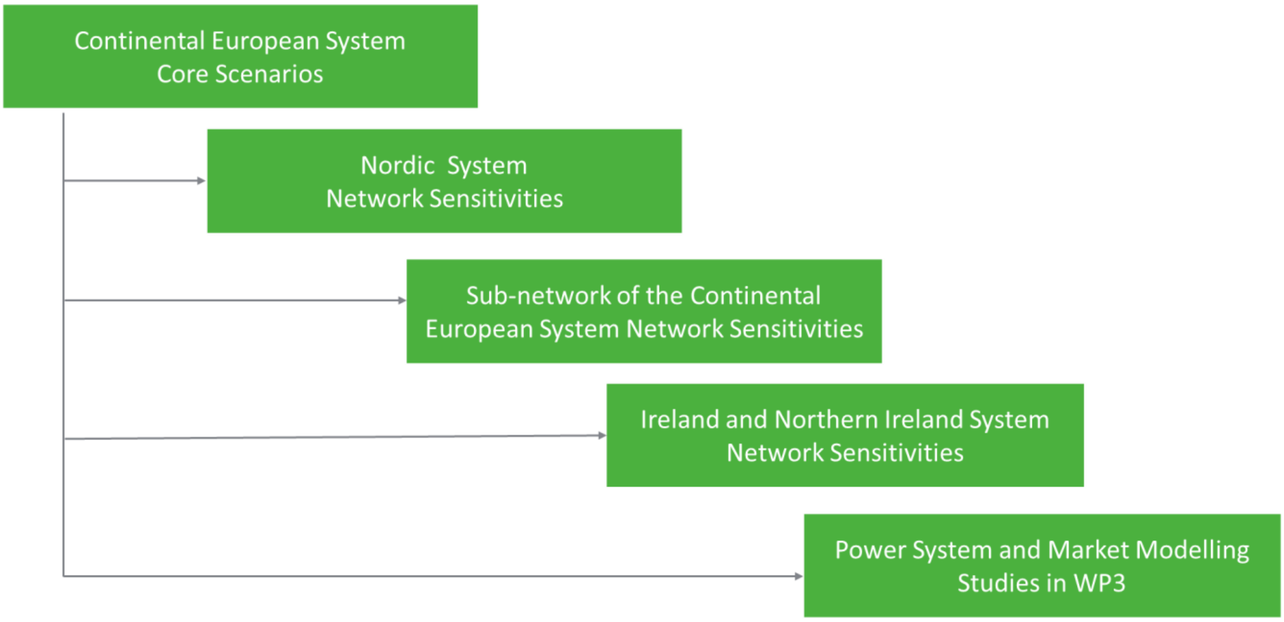


FIGURE 5: OVERVIEW OF THE APPLICATIONS OF THE EU-SYSFLEX SCENARIOS

2.2.1 CRITERIA FOR CHOOSING SCENARIOS

Following the review of scenario literature outlined in section 2.1, the following important criteria were determined for choosing the source data for the EU-SysFlex scenarios:

- The scenarios are consistent with the goals of the EU-SysFlex project (i.e. at least 50% RES-E for the European power system);
- A publicly available and complete dataset for each of the scenarios with individual EU-28 country breakdowns;
- The scenarios incorporate the targets, policies and directives of the European Union;
- The scenarios are recently developed; and
- There is a direct and coherent relationship between the two Core Scenarios to allow for easy comparisons – with one of the scenarios being more ambitious than the other in terms of the scale of the renewable energy production.

2.3 OVERVIEW OF THE EU-SYSFLEX SCENARIOS

Following a review of the scenarios discussed in section 2.1 against the criteria outlined in section 2.2.1, it was determined to base the two Core Scenarios for EU-SysFlex on the European Commission's EU Reference Scenario 2016 (European Commission, 2016) as they meet all of the aforementioned criteria. Furthermore, the EU Reference Scenario 2016 is an official scenario of the European Commission, and EU-SysFlex is a European Commission supported project. The EU Reference Scenario 2016 was prepared by national experts across all EU countries. It sets out a trajectory from 2020 – 2050, based on the European policy framework as of December 2014, with defined scenarios every five years. They integrate all of the European policies and directives, and meet the 2020 renewable energy targets set by the European Commission. In addition, they assume the successful implementation of the EU ETS and meet the CO_2 reduction targets for the projected years. This ties in well with the EU-SysFlex project as the project was funded from the competitive low-carbon energy call. The scenarios developed in the EU Reference Scenario 2016 are the result of a series of interlinked models combining technical and economic methods that have been peer-reviewed and/or have been used for numerous publications in peer-reviewed journals. They set out generation, demand, storage and interconnection portfolios which will be used in the development of EU-SysFlex scenarios. An overview of the EU-SysFlex scenarios is presented in Table 4.

Given the time horizon under consideration in the EU-SysFlex project, the 2030 scenario from the European Commission's EU Reference Scenario 2016 was used as the basis for the first EU-SysFlex scenario. This scenario was adapted for the purposes of the EU-SysFlex project and is called **Energy Transition**. For the second scenario, the European Commission's EU Reference Scenario 2016 with the most ambitious RES penetration was chosen. This was the European Commission's EU Reference Scenario for 2050, and the new EU-SysFlex scenario which is derived from it is called **Renewable Ambition**.

It is important that there is a direct relationship and coherence between harmonized scenarios to allow for an easy and direct comparison between the two core scenarios. The **Energy Transition** scenario is 65.5% carbon-free for the EU-28 countries. This includes 25% of energy which was produced from non-synchronous VRE sources (wind and solar generation). The **Renewable Ambition** scenario assumes 73.1% of generation comes from carbon-free sources, with 36% from non-synchronous VRE sources in the EU-28 countries. While, these figures are the average EU-28 percentages, they can be much higher for some individual member states. The percentages of RES-E as a proportion of demand across Europe for the two scenarios are 52% for the **Energy Transition** scenario and 66% for the **Renewable Ambition** scenario.

TABLE 4: OVERVIEW OF THE ENERGY TRANSITION AND RENEWABLE AMBITION SCENARIOS

EU 28 + CH + NO	**Energy Transition**	**Renewable Ambition**
Overall Demand	3 262 TWh	3 741 TWh
Overall Non-Synchronous VRE	859 TWh	1 441 TWh
Overall Renewable Generation	1 713 TWh	2 469 TWh
RES-E	52.5%	66.0%

2.3.1 EUROPEAN SUB-NETWORK SENSITIVITIES AND OTHER NETWORK SENSITIVITIES

The power system studies and assessments utilising the Core Scenarios **Energy Transition** and **Renewable Ambition** in WP2 will be complemented by additional Network Sensitivities. The Network Sensitivities have been developed to stress particular parts of the European network in order to examine further technical scarcities in greater detail. These Network Sensitivities are used to investigate more onerous or more ambitious generation and demand portfolios for specific areas and countries.

Many factors will affect deployment of renewables in the future including renewable support policies, siting requirements, costs and social acceptance. In addition, different types of renewable generating technologies may have different impacts on technical scarcities as a result of differences in generation patterns (e.g. wind and solar are primarily weather dependent, while hydro generation can vary seasonally), as well as technology-specific capabilities (e.g. hydro generation and biomass are synchronous generation types, while PV and wind are non-synchronous). Therefore, the Network Sensitivities have been tailored to further stress the European power system in specific areas which will undergo increased analysis and simulations.

It is intended that, in conjunction with the two consistent scenarios, these supplementary and complementary Network Sensitivities will ensure that all technical scarcities that can be expected in specific areas of the European grid are identified. In particular, these Network Sensitivities will, by increasing the levels of renewables, further stress the Nordic power system, sub-network of the Continental Europe system focused specifically on the Polish system and neighbouring countries, as well as the Ireland and Northern Ireland power system.

These additional Network Sensitivities will enable investigation of the impacts of specific portfolio changes on the power system. The different portfolios that will be assessed as part of the Network Sensitivities include detailed projections relating to economic growth, uptake of energy efficiency measures and new technologies on the demand-side, further variable renewable generation integration and conversion of conventional fossil fuel generating plants to renewable generating plants. For example, employment of these specific scenarios will result in a representation of the Ireland and Northern Ireland power system with instantaneous RES-E penetrations reaching up to 100%. These portfolios will form the basis of production cost simulations, which in turn will be utilised for detailed steady-state analysis, as well as frequency, dynamic, voltage and angular stability studies which will be used to identify technical scarcities.

Figure 6 provides a brief overview of the system-specific Network Sensitivities and each of these sensitivities is discussed in more detail later in this report. The development of these Network Sensitivities, entailed consultation with additional scenarios such as the ENTSO-E TYNDP 2018 scenarios and the e-highway2050 scenarios. These scenarios were used to check the consistency of the data used and to complement the EU Reference scenarios in developing other possible portfolios.

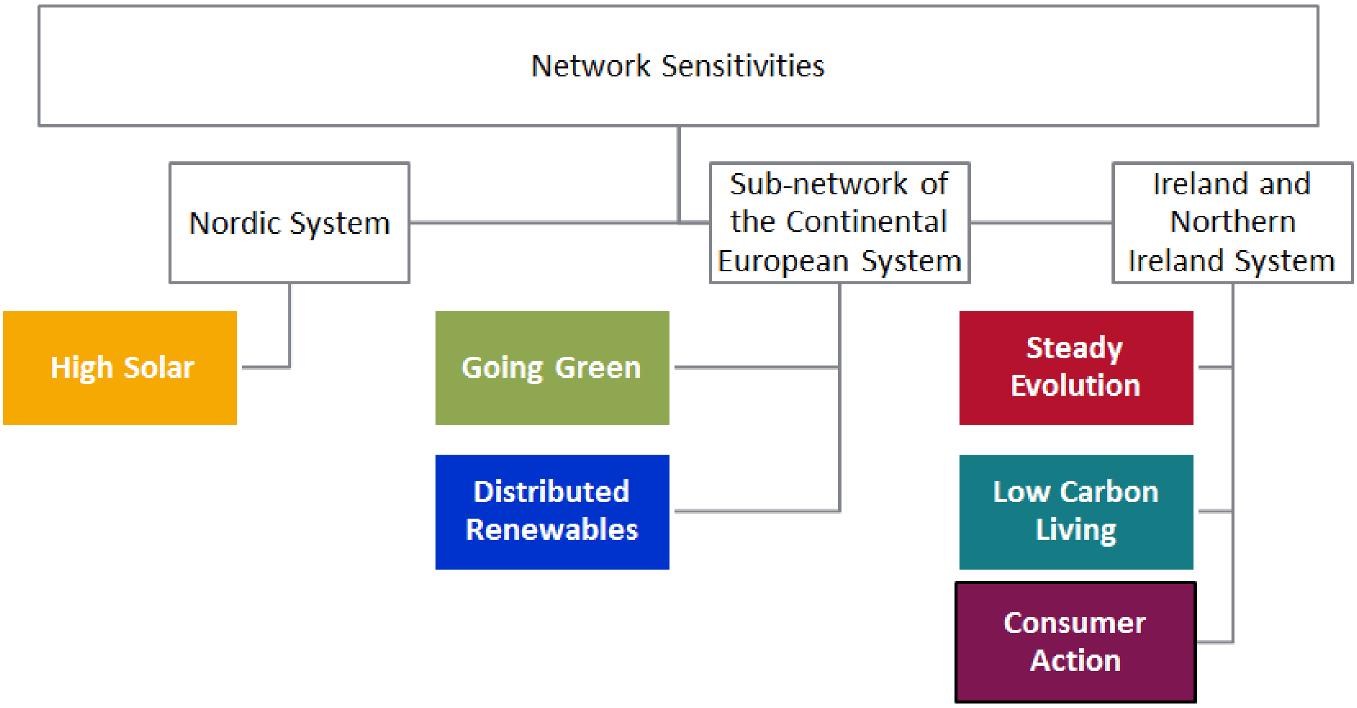


FIGURE 6: OVERVIEW OF THE EU-SYSFLEX NETWORK SENSITIVITIES

3. EU-SYSFLEX SCENARIOS – EUROPEAN POWER SYSTEM

The EU-SysFlex scenarios are based on the EU Reference Scenario 2016. Therefore, the starting point for these scenarios are the assumptions that all legally binding greenhouse gas (GHG) and RES targets for 2020 are achieved and that the policies agreed at EU and Member State level until December 2014 are implemented, as well as directives from early 2015. The development of the EU-Reference Scenario 2016 included interactions with experts from EU-28 Member States through a specific European Commission Reference Scenario expert group, namely for the modelling of energy, CO_2 emissions, transport, and sectorial activity projections. The underlying assumptions used in their development are also incorporated into the EU-SysFlex scenarios.

3.1 OVERVIEW OF THE EU-SYSFLEX SCENARIOS

This section gives a brief overview of the key policies that are integrated into the EU-SysFlex **Energy Transition** and **Renewable Ambition** scenarios.

3.1.1 CARBON EMISSION TARGETS

The modelling of the EU ETS includes the Market Stability Reserve adopted in 2015. The scenarios assume that the ETS emissions targets for 2020 have been achieved. A wide variety of additional policies are being implemented alongside ETS prices which influence the ETS sector such as RES support policies or energy efficiency measures. From 2040 onwards, the ETS price increases significantly. The rising costs of emitting CO_2 promote further investment in renewable technologies. The ETS emissions and ETS prices are given in Figure 7. The 2030 ETS price is used for the **Energy Transition** scenario and the 2050 ETS price is used for the **Renewable Ambition** scenario.

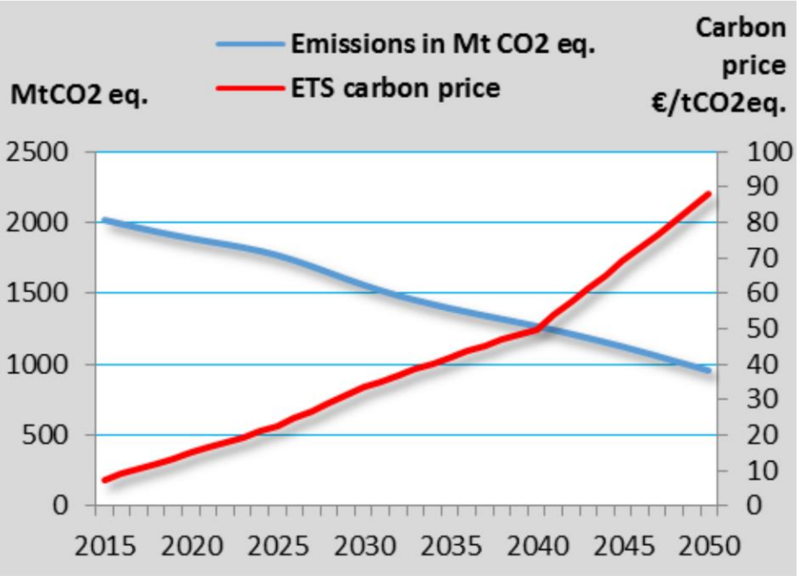


FIGURE 7: ETS EMISSIONS AND ETS CARBON PRICES ASSUMED IN THE EU REFERENCE SCENARIO 2016 (EUROPEAN COMMISSION, 2016)

The **Energy Transition** scenario has a total power generation that is 65.5% carbon-free for the EU-28 countries and the **Renewable Ambition** scenario has a 73.1% carbon-free production. While these figures are the average EU-28 percentages, they can be much higher for some individual member states as shown in Figure 8.

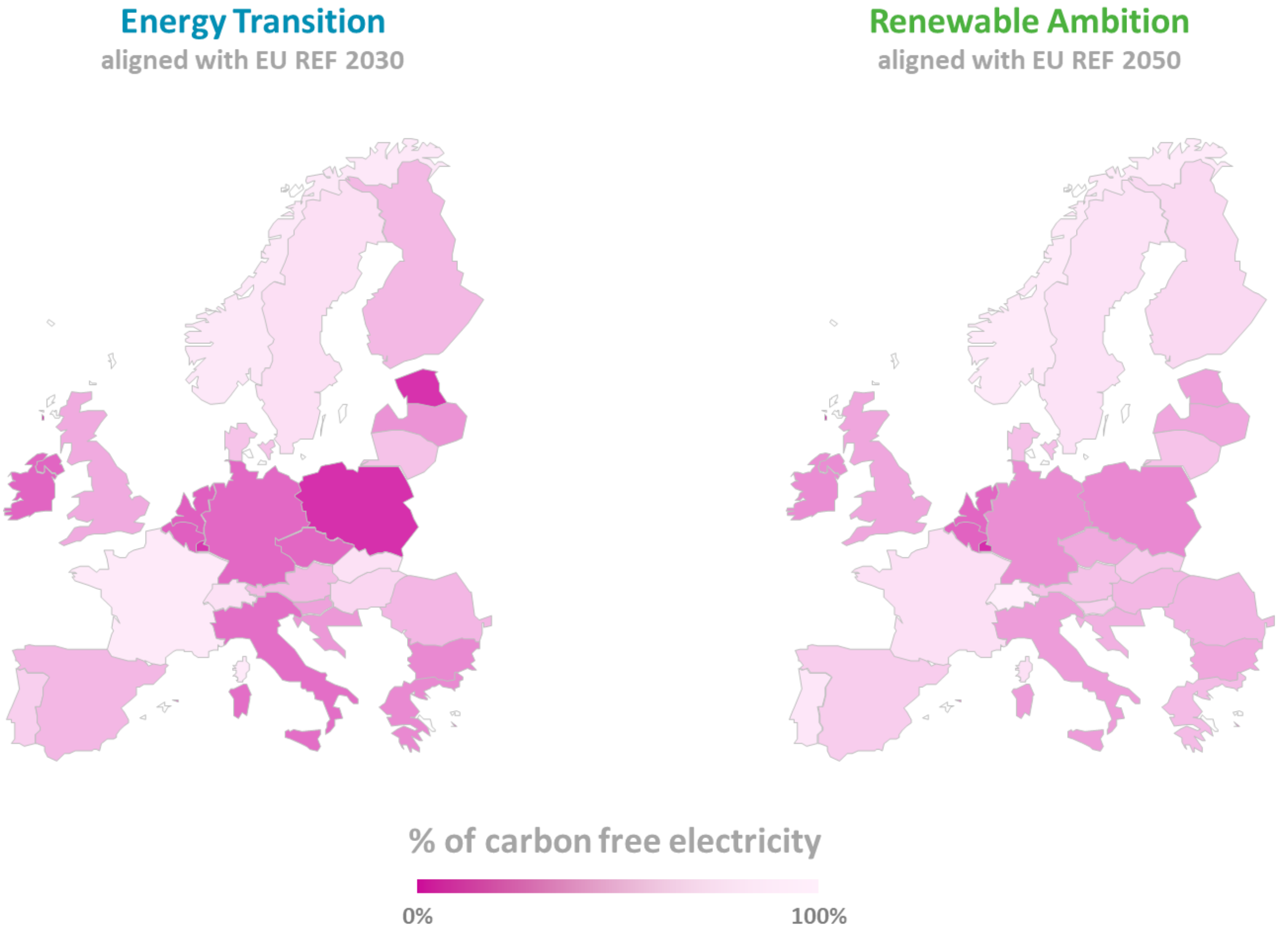


FIGURE 8: SHARE OF CARBON-FREE ELECTRICITY FOR ENERGY TRANSITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2030 (LEFT) AND RENEWABLE AMBITION ALIGNED WITH THE EU REFERENCE FOR 2050 (RIGHT)

3.1.2 ENERGY EFFICIENCY

The EU-SysFlex Scenarios incorporate energy efficiency policies adopted in recent years by the EU and Member States, including Ecodesign and Energy Labelling, the Energy Efficiency Directive (EED) and the Energy Performance of Buildings Directive (EPBD). This means that the scenarios consider a wide range of efficiency performance standards, as well as the interaction between different sectors. Better labelling and consumer information is taken into account and incite the consumer to select better technologies and to actively manage their energy use. For example, the rollout of smart metering allows for demand response so as to better manage electricity peak and high price situations, which in turn leads to an improved efficiency of the power system. The scenarios also take into account building renovation, with the public sector paving the way with best practices which are inciting private actors to follow.

3.1.3 RES POLICIES

The RES projections from the EU Reference Scenarios 2016, taken as the basis for the EU-SysFlex Scenarios, stem from consultations with Member States and integrate their projection trajectories of the RES shares by sector as expressed in the respective National Renewable Energy Action Plans (NREAPs). The framework integrates known direct RES feed-in tariffs and other RES enabling policies, such as priority access, grid development and streamlined authorisation procedures. The binding targets on RES for 2020 (20% share of gross final energy consumption from RES by 2020 and 10% of the transport sectors gross final energy consumption from RES by 2020) are assumed to be achieved. Beyond 2020, the RES development continues despite the fact that direct incentives are phased out because:

- Some RES technologies are becoming economically competitive;
- The carbon price is increasing through the ETS scheme; and
- The extension of the grid and the improvement in market balancing allow for higher RES penetration.

The **Energy Transition** scenario has a share of RES-E of 52% of the electricity demand, and the **Renewable Ambition** scenario has a share of 66%. While these figures are the average percentages for all countries modelled as part of the EU-SysFlex scenarios, the percentage of RES-E is higher for some individual countries and lower for others. Table 5 provides a summary of the renewable generation production, electricity demand and RES-E levels seen for all countries modelled in the two EU-SysFlex scenarios.

In addition to the percentage of RES-E in the two core scenarios, the percentage of variable non-synchronous renewable resources is of particular interest to the EU-SysFlex project. As highlighted in the EU-SysFlex D2.1 – State-of-the-Art Literature Review of System Scarcities at High Levels of Renewables, the challenges of integrating high levels of renewable generation are primarily seen at times of high non-synchronous generation penetration (EU-SysFlex, 2018). Therefore, within the two core scenarios, the hours which have the highest levels of non-synchronous generation will be examined in detail through technical simulations to understand future system scarcities.

Table 6 provides a summary of the carbon-free generation and non-synchronous variable renewable generation for each of the European country considered in the EU-SysFlex scenarios. This is further illustrated in Figure 9, which demonstrates the increase in non-synchronous VRE for each European country between the **Energy Transition** and **Renewable Ambition** scenarios.

TABLE 5: PERCENTAGES OF RENEWABLE ENERGY PRODUCTION IN THE ENERGY TRANSITION AND RENEWABLE AMBITION SCENARIOS AS A PERCENTAGE OF DEMAND

	Energy Transition			Renewable Ambition		
Country	**RES production (TWh_e)**	**Demand (TWh_e)**	**%RES**	**RES production (TWh_e)**	**Demand (TWh_e)**	**%RES**
AT	62	73	85%	73	83	88%
BE	29	89	32%	41	108	37%
CH	45	61	74%	74	56	132%
CZ	9	66	14%	16	79	21%
DE	267	559	48%	385	580	66%
DK	29	36	80%	35	44	80%
ES	163	257	63%	282	291	97%
FI	43	84	51%	50	96	52%
FR	211	469	45%	362	548	66%
HU	3	39	8%	9	47	19%
IE	14	28	48%	21	34	63%
IT	148	314	47%	273	395	69%
LU	1	8	12%	2	12	14%
NL	50	116	43%	67	133	50%
NO	155	117	132%	160	110	145%
PL	40	168	24%	71	202	35%
PT	42	48	88%	50	51	98%
SE	113	144	78%	133	166	80%
SK	7	31	21%	10	34	31%
UK	176	356	49%	201	438	46%
Total	**1 607**	**3 063**	**52%**	**2 315**	**3 507**	**66%**

TABLE 6: CHARACTERISTICS OF THE EU-SYSFLEX SCENARIOS FOR THE 28 MEMBER STATES, SWITZERLAND AND NORWAY, FOR CARBON-FREE ELECTRICITY AND VARIABLE NON-SYNCHRONOUS RENEWABLE ENERGY AS PART OF THE ELECTRICITY PRODUCTION. (VRE = VARIABLE RENEWABLE ENERGY)

	Energy Transition				Renewable Ambition			
Country	**% carbon - free**	**% VRE**	**VRE of which**		**% carbon - free**	**% VRE**	**VRE of which**	
			% Wind	**% Solar**			**% Wind**	**% Solar**
EU-28	**65**	**24**	**72**	**28**	**73**	**35**	**70**	**30**
AT	78	17	75	25	81	23	75	25
BE	40	32	83	17	41	33	84	16
BG	57	18	63	37	70	23	57	43
CH	94	13	26	74	100	18	27	73
CY	29	26	32	68	41	38	33	67
CZ	43	4	28	72	70	5	38	62
DE	44	31	68	32	60	43	70	30
DK	81	58	96	4	80	58	97	3
EE	21	11	100	0	67	42	100	0
ES	77	42	60	40	86	71	54	46
FI	77	8	100	0	91	8	100	0
FR	98	20	67	33	94	38	69	31
GR	57	46	63	37	78	66	58	42
HR	64	16	56	44	73	31	46	54
HU	90	2	90	10	77	9	85	15
IE	42	36	100	0	59	49	100	0
IT	46	21	49	51	65	36	41	59
LV	61	9	100	0	70	19	100	0
LT	81	6	93	7	82	14	97	3
LU	22	14	81	19	18	13	87	13
MT	13	13	-	100	22	20	13	87
NL	40	24	85	15	43	29	88	12
NO	97	10	100	-	99	12	96	4
PL	20	11	100	0	57	18	99	1
PT	87	41	79	21	96	52	71	29
RO	76	21	83	17	75	25	74	26
SE	93	13	100	0	94	14	100	0
SI	67	6	29	71	87	6	31	69
SK	94	2	4	96	84	4	23	77
UK	71	26	91	9	70	28	93	7

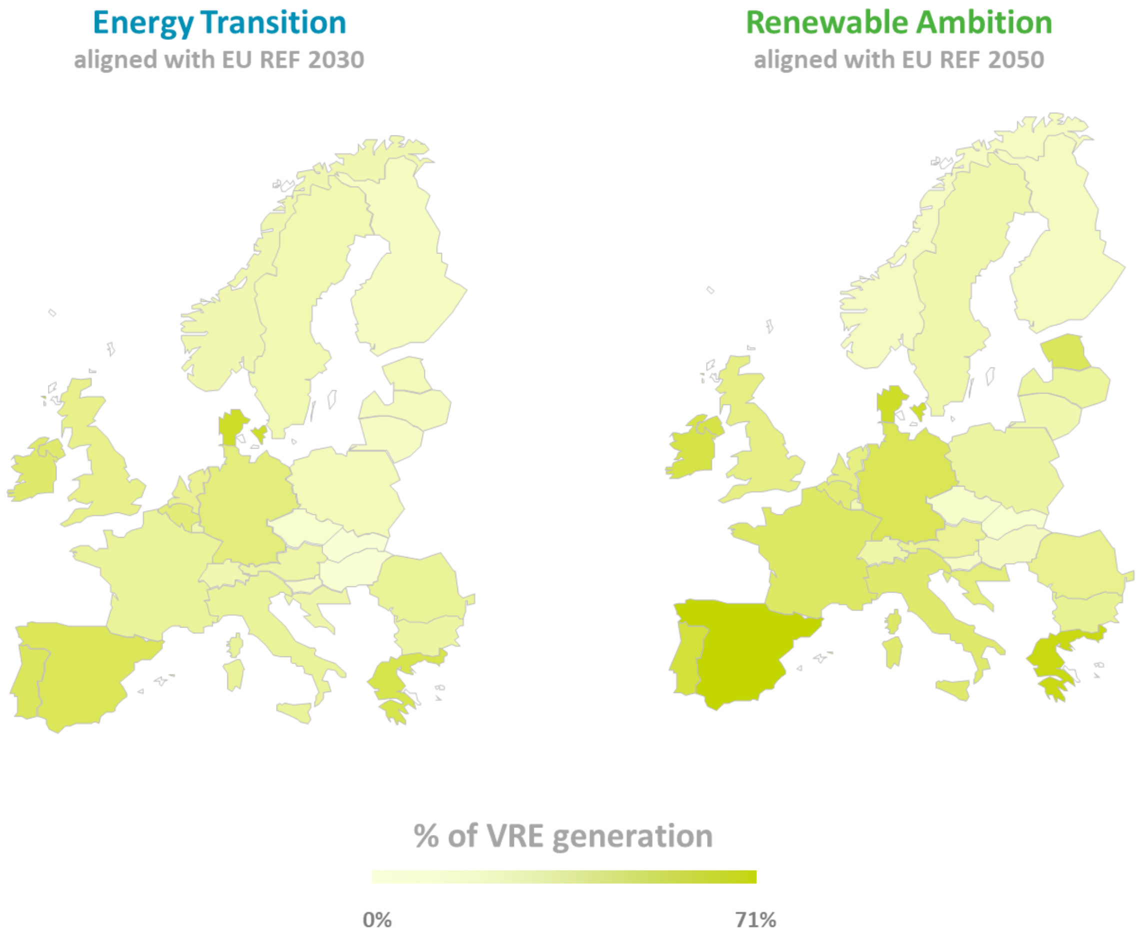


FIGURE 9: SHARE OF VARIABLE NON-SYNCHRONOUS RENEWABLE GENERATION (WIND AND SOLAR) FOR POWER GENERATION FOR ENERGY TRANSITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2030 (LEFT) AND RENEWABLE AMBITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2050 (RIGHT)

The EU-SysFlex scenarios allow us to identify several decarbonisation strategies:

- **Decarbonisation based on a power generation mix with a high share of variable RES, i.e. wind and solar energies:** Wind and solar technologies are replacing non carbon-free sources such as coal or gas, as shown in Figure 10. The share of variable renewables in these systems can be very high. Spain, Greece, Denmark, Portugal and Ireland reach a share of VRE higher or equal to almost 50% in the **Renewable Ambition** scenario. Portugal has the characteristics to couple a large share of variable renewables with a large share of hydro, allowing it to reach a carbon-free level of 96%. In Spain, the carbon-free share reaches 71%, split almost equally between solar and wind, and the 14% share of gas subsides as the share of biomass and hydro remains relatively small. The generation split for Greece is similar to that of Spain. Denmark and Ireland are relying almost exclusively on wind generation as well as biomass to lower the share of non carbon-free generation, typically coal or gas fired power plants. Belgium, Estonia, Germany, the Netherlands, and to some extent Italy, rely on a high share of variable renewable energy to lower the carbon intensity of their power generation mix. Biomass plays an important role for Denmark, Estonia and Belgium.

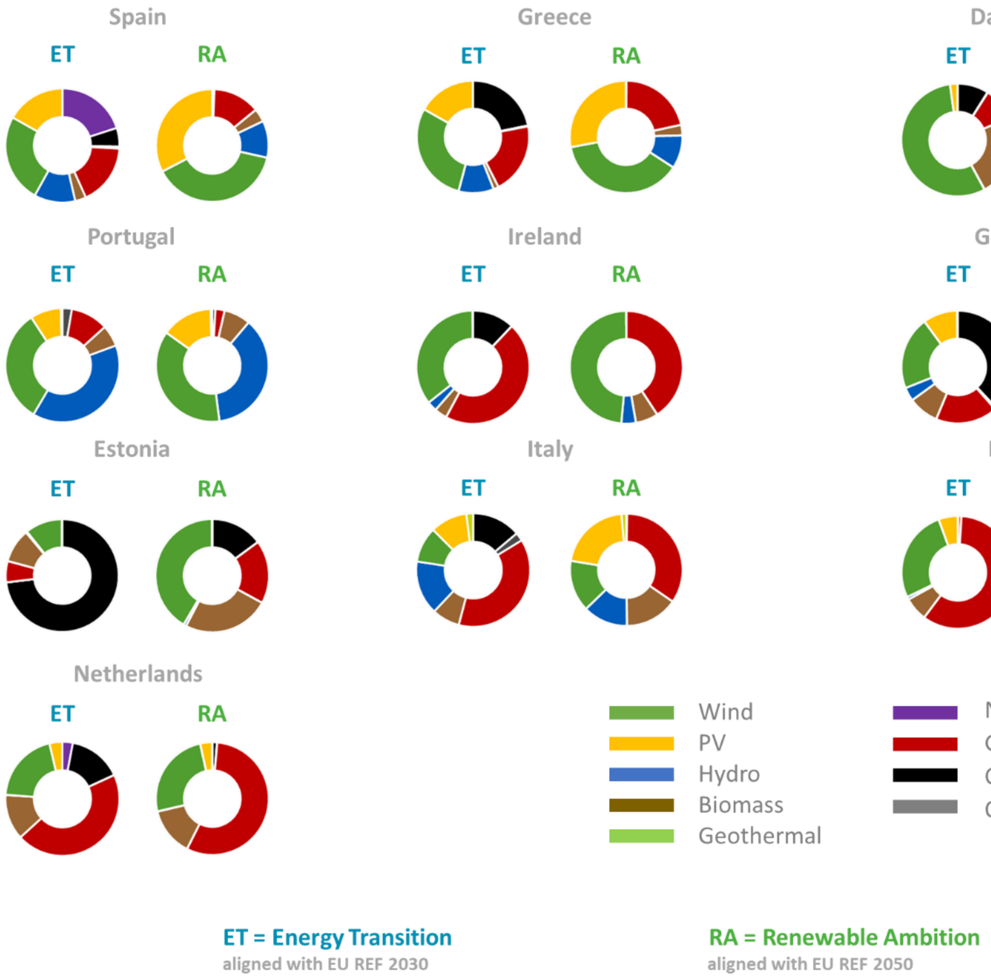


FIGURE 10: COMPARISON OF TOTAL ANNUAL POWER PRODUCTION BY FUEL TYPE FOR ENERGY TRANSITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2030, AND RENEWABLE AMBITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2050, FOR ALL COUNTRIES RELYING PREDOMINANTLY ON VARIABLE RENEWABLE ENERGIES

- **Decarbonisation based on a power generation mix of variable renewable energies in conjunction with CO_2-free dispatchable energies:** Wind and solar energies are combined with other carbon-free technologies, renewable or nuclear, to replace non carbon-free energies such as coal or gas as shown in Figure 11. Generally, the power mix of the countries of Figure 11 have a low carbon intensity in **Renewable Ambition**, upwards of 57% carbon-free, with 5 countries being upwards of 90% carbon-free and more than half being upwards of 80% carbon-free. These countries rely on a combination of hydroelectricity where available, biomass and nuclear energies, along with wind and solar. The choice of dispatchable energies depends mainly on their local resources.

FIGURE 11: COMPARISON OF TOTAL ANNUAL POWER GENERATION BY FUEL TYPE FOR ENERGY TRANSITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2030, AND RENEWABLE AMBITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2050, FOR ALL COUNTRIES RELYING ON CARBON-FREE, DISPATCHABLE TECHNOLOGIES IN CONJUNCTION WITH VARIABLE NON-SYNCHRONOUS RENEWABLE GENERATION

3.2 MODELING OF EU-SYSFLEX SCENARIOS

The EU-SysFlex dataset for the two core scenarios, **Energy Transition** and **Renewable Ambition**, are consistent with the EU reference scenarios, i.e. they broadly comply with the data published by these scenarios (for each country, annual production by energy and capacity sector, and net import).

The technical consistency of these scenarios is then validated using CONTINENTAL, an EDF State-of-the-Art Unit Commitment software suite, which was used for the study on integrating 60% Renewable Energy into the European System (Burtin & Silva, 2015). This suite is an integrated generation and market simulation system. It balances electricity supply and demand over the medium-term, on numerous scenarios reflecting the uncertainty, for a set of interconnected zones, minimising the overall production cost. Figure 12 shows the different steps of the CONTINENTAL model, as well as the breadth of input and output data.

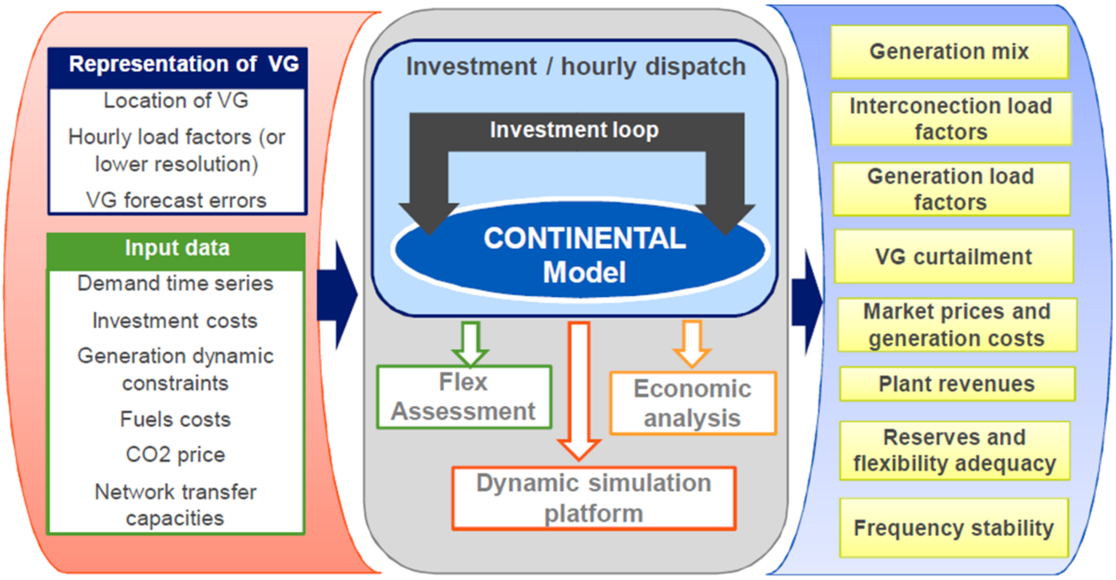


FIGURE 12: SOFTWARE SUITE WITH AN INVESTMENT LOOP AND A UNIT COMMITMENT MODEL

First an investment loop ensures that the power system that is modelled does not have excessive hours of unserved energy, and complete the generation mix if needed in the most cost-effective way. The Unit Commitment model then proceeds in two steps:

1. First, it determines the strategy for using hydraulic stocks (water placement), by calculating “water values" for each period and stock level and for each scenario, using a dynamic stochastic programming method. These water values will then be assimilated to variable costs.
2. It then calculates the electric generation program by zone minimising the overall margin cost of the system and respecting the various constraints of the power system: supply-demand balance at each hour, maximum interconnection capacities, dynamic constraints related to the flexibility of thermal units (minimum power, start-up costs, minimum on/off time, load rise and fall gradients, etc.), constraints related to the primary and secondary reserve services.

This tool requires data more detailed and extensive than the one provided by the report on the EU Reference Scenarios, such as hourly details of consumption data, solar, wind and run-of-river hydropower production, water inflows for the lakes, etc. In addition, the uncertainty coming from weather patterns is taken into account using a set of over 50 climate years, which are projections into the future of historical data. The hourly data for wind and solar are recomputed using the historical wind speeds and solar radiation on a prospective distribution of installed capacities. The SETIS dataset (European Commission, 2018) is used to give hourly capacity factors for wind and solar, so that all partners of EU-SysFlex project have access to the same data. The demand for each climate year was then recalculated using the historical temperature data and the projected new uses. Therefore, the weather patterns are consistent across the dataset, which is important for the results of the study.

The CONTINENTAL model also requires data for conventional plants such as the technical characteristics of the thermal units (efficiency range, variable costs, planned and forced outage rate, start-up cost, minimum on/off time, etc.), interconnection characteristics, number of electric vehicles (for demand), commodity prices. This additional information was collected from other public scenarios consistent with the EU Reference Scenarios (e.g. TYNDP), or from historical data (e.g. hydraulic). The first step of the EU-SysFlex scenario creation is to create an hourly dataset broken down into numerous scenarios (reflecting the different types of uncertainties – climate and forced outages) where the installed capacities for the power system are matching the EU Reference Scenario.

Following this, the Unit Commitment software seeks to optimally schedule the generation of both thermal and hydro generation plants to meet system net demand (taking account of renewable generation and interconnectors) and indicates the number of hours of unserved energy in the system. The initial data set is then adjusted iteratively - for example by adding advanced thermal means, or by tuning some parameters such as maintenance rates, merit order between gas and coal, etc. - to obtain thermal energy targets as close as possible to the annual targets of the EU scenarios Reference Scenario as well as a number of unserved energy hours that meet a criteria of 3 hours of unserved energy on average for all European countries (European Commission, 2016). This iterative process requires a lot of fine-tuning to deviate only marginally from the initial values from the EU-Reference 2030 and 2050 scenarios and to develop the **Energy Transition** and **Renewable Ambition**.

It should be noted that, as shown in Table 7 in the CONTINENTAL Unit Commitment model, the modelling is not developed for all EU-28 countries. It does however include 20 countries: Austria, Belgium, The Czech Republic, Denmark, Finland, France, Germany, Hungary, Ireland, Italy, Luxembourg, The Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland, and the United Kingdom.

The results for the total annual power production by primary energy source for **Energy Transition** and **Renewable Ambition** obtained with the modelling above is shown in Figure 13 and Figure 14. These graphs were produced from averaging the hourly production for each country by primary energy source over 165 separate year-long simulations. Each of these simulations represents a year with different climatic conditions and generator outages. The model includes technical generator constraints as well as locational reserve constraints. There is excellent alignment between the energy production values as quoted in the EU References Scenarios and the two EU-SysFlex scenarios, **Energy Transition** and **Renewable Ambition**[1].

The output of this detailed modelling of the European power system is production schedules at an hourly resolution for a large range of climate years. This will allow the EU-SysFlex project to carry out state-of-the-art technical and economic studies of a system with a large amount of variable renewables, and make key contributions to the final flexibility roadmap of the EU-SysFlex project.

TABLE 7: COUNTRIES INCLUDED IN THE SCENARIOS AND THE CONTINENTAL MODEL

	EU Reference Scenario 2016	EU-SysFlex Scenarios	CONTINENTAL Model
Countries Included	EU-28 only	EU-28 + CH + NO	AT, BE, CH, CZ, DE, DK, ES, FI, FR, HU, IE, IT, LU, NL, NO, PL, PT, SE, SK, UK

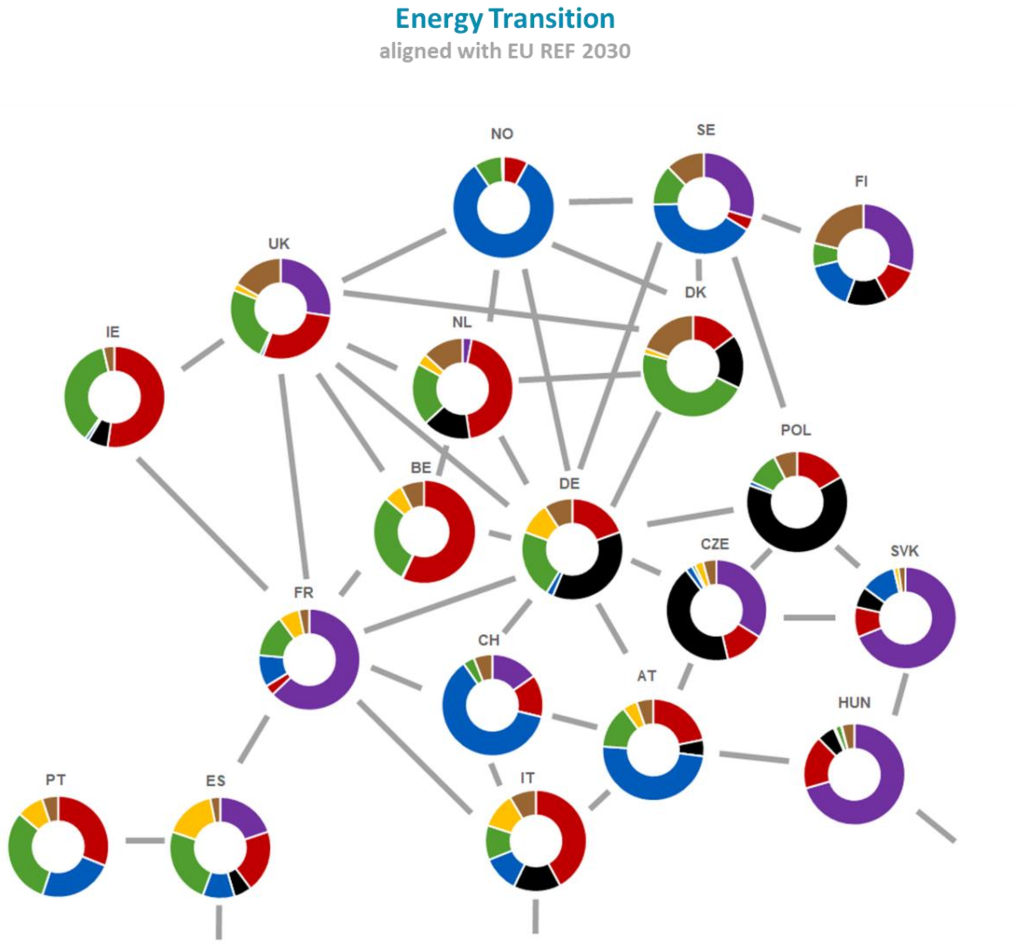


FIGURE 13: TOTAL ANNUAL POWER PRODUCTION FOR THE ENERGY TRANSITION SCENARIO ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2030

---

[1] For some countries with lower electricity production relative to the overall European power system, there were some small discrepancies for fuels where only a few plants are installed. This is due to the sizing of the plants, which have to be consistent between countries.

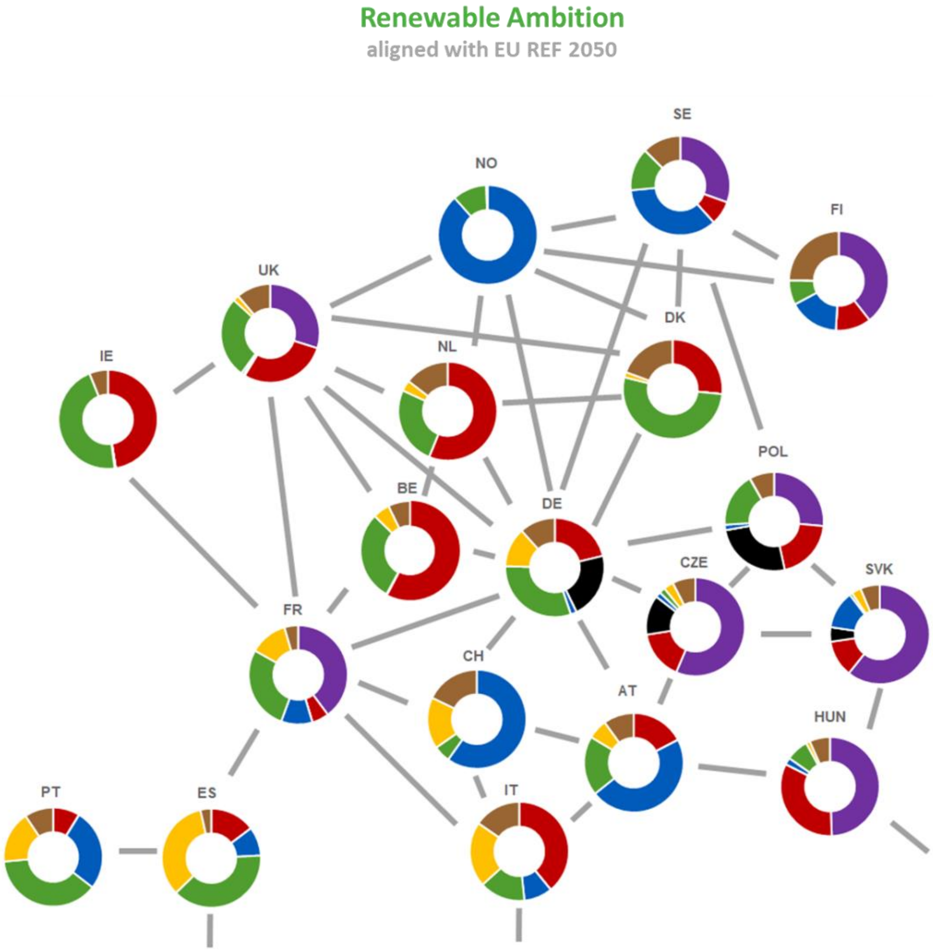


FIGURE 14: TOTAL ANNUAL POWER PRODUCTION FOR RENEWABLE AMBITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2050

In the analysis of the assumptions in the next section, data from the EU Reference Scenarios will be utilised where needed to represent all EU-28 countries. In addition, Norway and Switzerland are added.

3.3 ASSUMPTIONS FOR EU-SYSFLEX SCENARIOS

3.3.1 ELECTRICITY DEMAND COMPONENTS AND GROWTH

The demand in the EU-SysFlex Core Scenarios, based on the EU-Reference scenarios, incorporates macroeconomic projections as well as projected sectorial trends, i.e. industry, residential and transport. It also takes into account the energy efficiency policies adopted in recent years by the EU and Member States. The final electricity demand increases under the combined effect of a shift towards electricity for heating and cooling, of the electrification of transport through the electric vehicle, and an always larger number of appliances and digital products in the residential and tertiary sectors. The transport sector also sees electrification through the development of electric vehicles and rail. Overall, the electricity demand is assumed to grow at a rate of 0.7% per annum between 2020 and 2050, giving a higher demand for **Renewable Ambition** compared to **Energy Transition**.

3.3.1.1 ELECTRICITY DEMAND GROWTH

The underlying assumptions relating to population growth in the European Commission's References Scenarios naturally have an impact on the demand growth assumptions utilised in the scenarios. The European Union population is projected to increase in the coming decades, accompanied by increased life expectancy and an increase in net inward migration.

In conjunction with this population growth, EU gross domestic product (GDP) is also projected to grow at a stable rate. In addition, continuing recovery of the European economy is expected, accompanied by lower energy prices. This is expected to lead to increased demand as well as an increase in the use of electrical appliances in the residential and commercial sectors. This combined with the trends towards greater electrification of heating and cooling, as well as transport, will drive electrical demand upwards despite the ambitious increase in energy efficiency set forth by the EU targets through the Energy Efficiency Directive (EED) and the Energy Performance of Buildings Directive (EPBD).

3.3.1.2 ELECTRIFICATION OF RESIDENTIAL AND TERTIARY SECTORS

The residential and tertiary sectors see their demand for energy decrease compared to 2010 through the different energy efficient policies in place and despite a significant growth in comfort and services. The decrease is explained by the fact that heating represents the highest share of energy consumptions for these sectors and by the fact that the number of renovations of buildings and the stricter building codes for new dwellings making up for a better thermal insulation allows for a more efficient use of heating. Electricity demand increases as the number of albeit very energy efficient appliances increases and the shares of heating and cooling increase. Heat pumps are developing even in countries where the market share of electricity in heating was historically very low but where renewable energies are increasing rapidly.

3.3.1.3 ELECTRIFICATION OF TRANSPORT

The transport sector represents the largest share in the final energy consumption. It is developing significantly, particularly for passenger and freight transport, following growth in economic activity. However, after an initial growth, individual passenger transport slows down as the market becomes saturated, congestion levels are rising and fossil fuel prices are increasing, while passenger rail transport sees an uptake with new high speed trains and the upgrade of existing infrastructure. The transport sector sees a shift towards electricity through several vectors. Electric vehicles and Plug-in Hybrid Electric vehicles are developing as a result of national and EU policies. In particular, some Member States have put in place strong incentives and the penetration levels are higher. Table 8 shows the assumptions, taken from the TYNDP 2018 (ENTSO-E, 2018), used for the EU-SysFlex Scenarios.

Furthermore, diesel powered trains are switched to electricity where possible. The advent of increased numbers of electric vehicles, as well as digitally connected appliances, allow for new demand response possibilities. In particular, the EU-SysFlex Core Scenarios take into account different types of charging for electric vehicles as shown in Figure 15.

TABLE 8: NUMBER OF ELECTRIC VEHICLES BY COUNTRY IN THE TWO EU-SYSFLEX SCENARIOS (ENTSO-E, 2018)

Country	Energy Transition	Renewable Ambition
AT	629 453	1 806 126
BE	456 870	2 033 698
CH	1 145 169	2 953 160
CZ	611 176	1 923 221
DE	5 400 000	15 422 654
DK	495 803	1 180 196
EE	46747	N/A
ES	2 425 000	8 529 362
FI	269 444	960 315
FR	6 349 063	14 500 448
HU	246 014	1 302 051
IE	313 591	957 782
IT	6 244 147	15 034 613
LT	117 786	N/A
LU	46 000	165 942
LV	93 120	N/A
NL	1 013 127	3 071 554
NO	1 076 870	1 789 128
PL	2 671 014	6 489 376
PT	694 778	1 657 273
SE	716 169	2 131 270
SK	238 937	869 720
UK	4 759 302	13 500 250

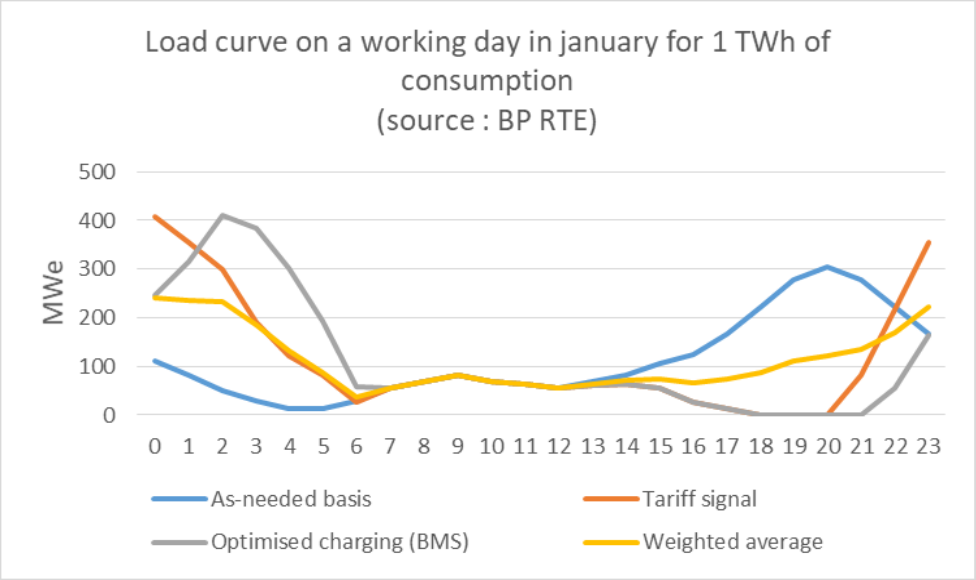


FIGURE 15: DIFFERENT LOAD CURVE PROFILE FOR ELECTRIC VEHICLES (RTE, 2017)

3.3.1.4 ELECTRIFICATION IN THE INDUSTRIAL SECTOR

The industrial sector is shifting to less carbon intensive fuels, as the ETS carbon price is rising, and in particular the share of electricity is increasing. In addition, a number of countries in Europe, including Ireland, are expecting rapid and unprecedented deployment of large scale data centre facilities. Data centres are exceptionally large energy consumers and consequently contribute to increasing demand projections

3.3.1 ELECTRICITY SUPPLY

The EU-SysFlex Core Scenarios include investments in generation capacity for all Member States, as well as planned lifetime extensions or planned decommissioning of generation. For investments in RES, CCS technologies, and storage, country-specific potentials are considered. The total installed generation capacity for the EU-28 countries is projected to increase moderately in **Energy Transition** in comparison to today's levels. The **Renewable Ambition** scenario sees much larger developments of wind and solar capacities.

The share of fossil fuel production, such as coal or gas, in the EU-28 countries, as well as in Switzerland and Norway, decreases between the **Energy Transition** scenario and the **Renewable Ambition** scenario. This decrease in the fossil fuel production is weighted in favour of coal generation, as gas–fired generation is less CO_2 intensive than coal. The increase in renewable production is between the **Energy Transition** scenario and the **Renewable Ambition** scenario dominated by wind and solar generation.

3.3.1.1 FOSSIL FUELS

In the Core Scenarios, the use of fossil fuels for European electricity production decreases between the **Energy Transition** scenario and the **Renewable Ambition** scenario, as the coal production decreases while the production by gas turbine increases.

3.3.1.1.1 COAL

The coal production decreases sharply in Europe between the **Energy Transition** scenario and the **Renewable Ambition** Scenario (see Figure 16). In Energy Transition, the share of coal in the power generation mix is higher than 8% for 13 countries: Estonia, Poland, Czech Republic, Germany, Bulgaria, Slovenia, Greece, The Netherlands, Italy, Ireland, Romania, Finland and Denmark. It is higher than 25% for the 5 first countries of the list, and higher than 50% for Poland and Estonia with a maximum share reaching 73%. In **Renewable Ambition**, coal production is mainly located in Member States that have substantial coal generation today and a large amount of indigenous resources, and only 6 countries have a share higher than 8% (Poland, Germany, Bulgaria, Czech Republic, Estonia and Romania) with the highest share in the mix being 25% in Poland. Whereas in Energy Transition, CCS technology is at the stage of demonstration plants, about two thirds of the coal plants in **Renewable Ambition** are retrofitted with CCS, where the investments are economically driven by increasing ETS prices. In the Continental European model, 15% of the total energy production comes from coal in in the **Energy Transition** Scenario while this drops to roughly 6% in the **Renewable Ambition** Scenario.

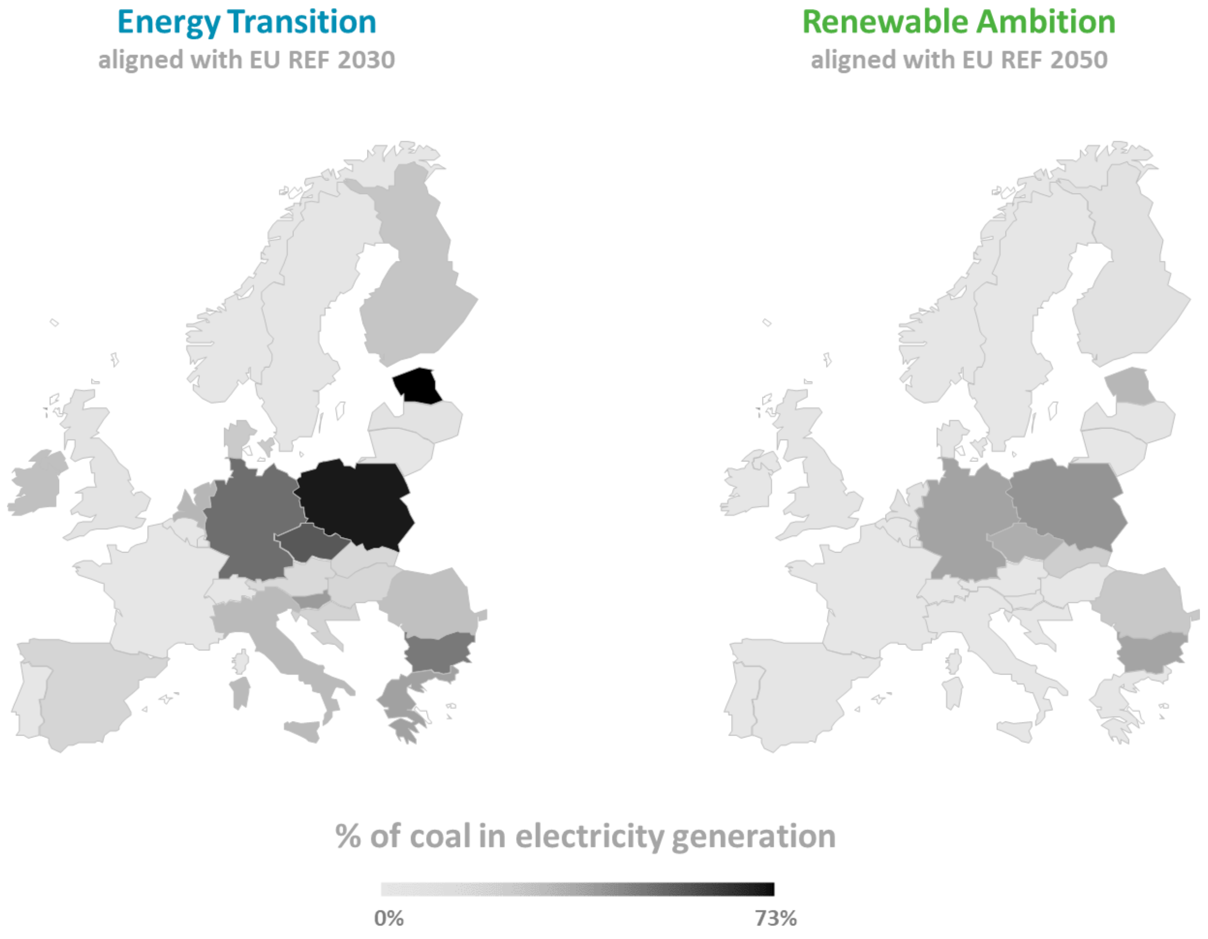


FIGURE 16: SHARE OF ELECTRICITY GENERATION FROM COAL FOR ENERGY TRANSITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2030 (LEFT) AND RENEWABLE AMBITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2050 (RIGHT)

3.3.1.1.2 GAS

The installed capacity, as well as the production of gas-fired plants, is projected to increase, since gas plants are less CO_2-intensive than other fossil fuels and generate power when renewables are not (see Figure 17). However, the share of gas production remains fairly stable with 18% of the production in **Energy Transition** and roughly 21% in **Renewable Ambition**. About a third of the capacity corresponds to refurbishments and most of the new plants are CCGTs.

In **Energy Transition**, the gas share is higher than 17% in 15 countries: Malta, Luxembourg, Cyprus, Belgium, Ireland, The Netherlands, Italy, Latvia, Croatia, the United Kingdom, Greece, Lithuania, Austria, Germany, and Spain, and the first 6 countries have a share that is higher than 40%. In **Renewable Ambition**, 18 countries have a share higher than 17%: Luxembourg, Malta, Belgium, Cyprus, The Netherlands, Ireland, Italy, the United Kingdom, Latvia, Croatia, Hungary, Greece, Austria, Germany, Denmark, Lithuania, Estonia, Poland, with the first six countries having a share higher than 40%.

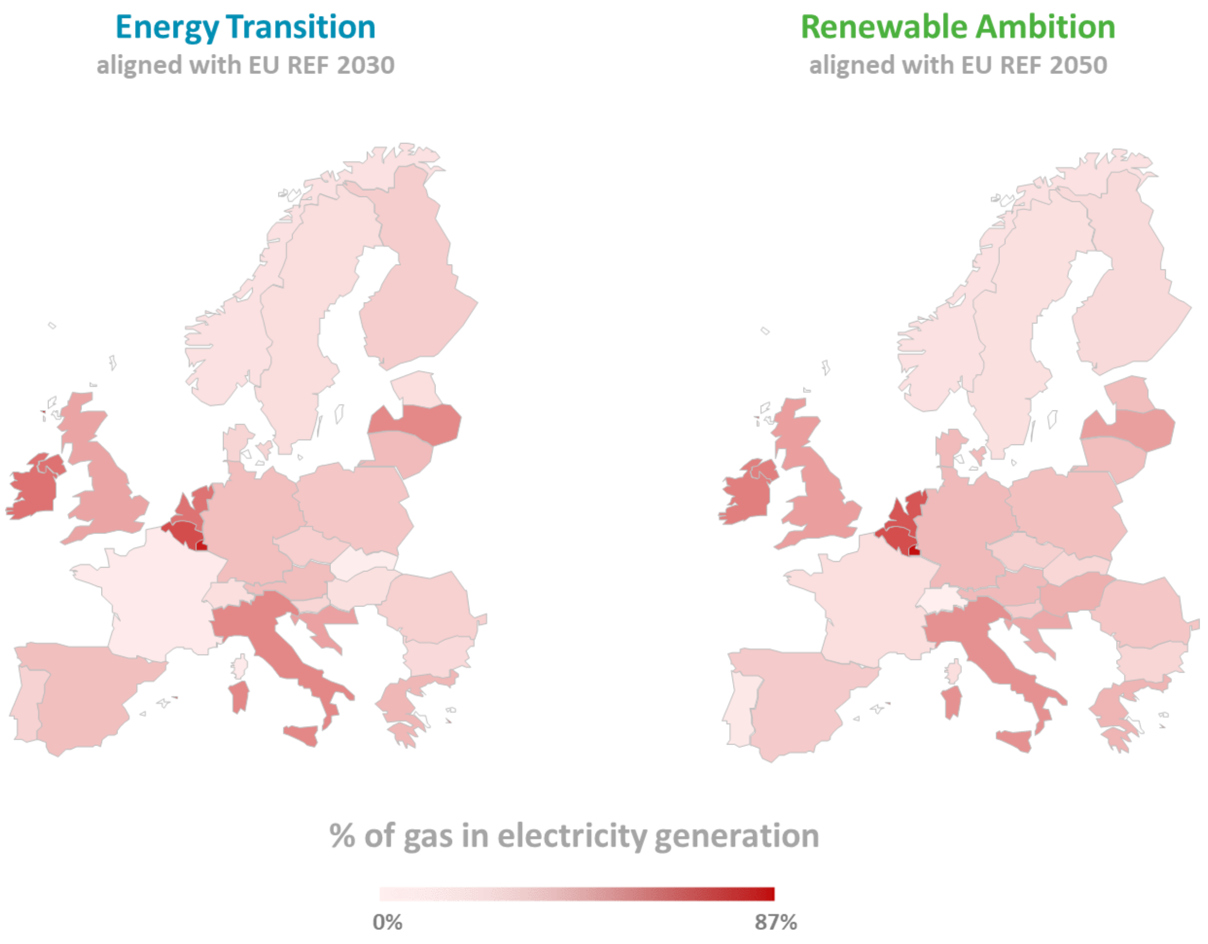


FIGURE 17: SHARE OF ELECTRICITY GENERATION FROM GAS FOR ENERGY TRANSITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2030 (LEFT) AND RENEWABLE AMBITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2050 (RIGHT)

3.3.1.1.3 OTHER FOSSIL FUELS

Oil capacity is representing a very small share in **Energy Transition** at 1%, and it is further substantially decreased in **Renewable Ambition**.

3.3.1.2 NUCLEAR

The share of nuclear production remains approximately stable between the **Energy Transition** scenario and the **Renewable Ambition** scenario, representing 21% in **Energy Transition** and roughly 18% in **Renewable Ambition.** About a quarter of the investments between **Energy Transition** and **Renewable Ambition** are retrofits and 75% are new investments for building new plants, most of them on existing sites. However, a few of the projects are on new sites. In **Energy Transition**, 14 countries have nuclear production: Hungary, Slovakia, Lithuania, France, Czech Republic, Romania, Finland, Slovenia, Bulgaria, Sweden, the United Kingdom, Spain, Switzerland, The Netherlands, with 12 countries having a share higher than 20% (see Figure 18). In **Renewable Ambition**, 12 countries have nuclear generation with a share higher than 25%: Slovakia, Hungary, Czech Republic, Lithuania, Slovenia, Finland, France, Bulgaria, Sweden, the United Kingdom, Poland, and Romania.

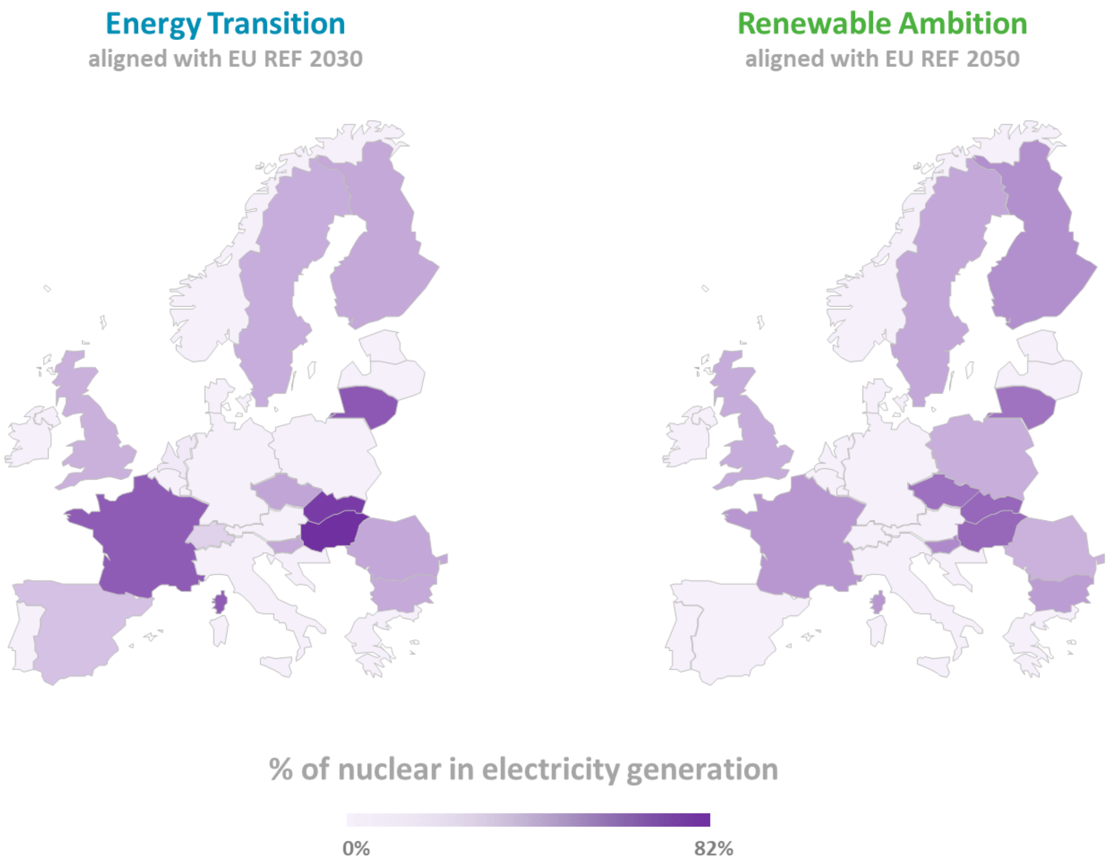


FIGURE 18: SHARE OF ELECTRICITY GENERATION FROM NUCLEAR FOR ENERGY TRANSITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2030 (LEFT) AND RENEWABLE AMBITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2050 (RIGHT)

3.3.1.3 HYDROELECTRICITY

Hydraulic production represents about 10% of the total net generation, but the capacity of installed plants is increasing by roughly 9 GW between **Energy Transition** and **Renewable Ambition** with investments essentially in small run-of-river plants. The 8 largest hydro producers in Europe are Norway, Switzerland, Austria, Croatia, Latvia, Sweden and Portugal (see Figure 19). At least 30% of their electricity comes from hydro, and the share rises to over 50% for Austria, Switzerland and Norway.

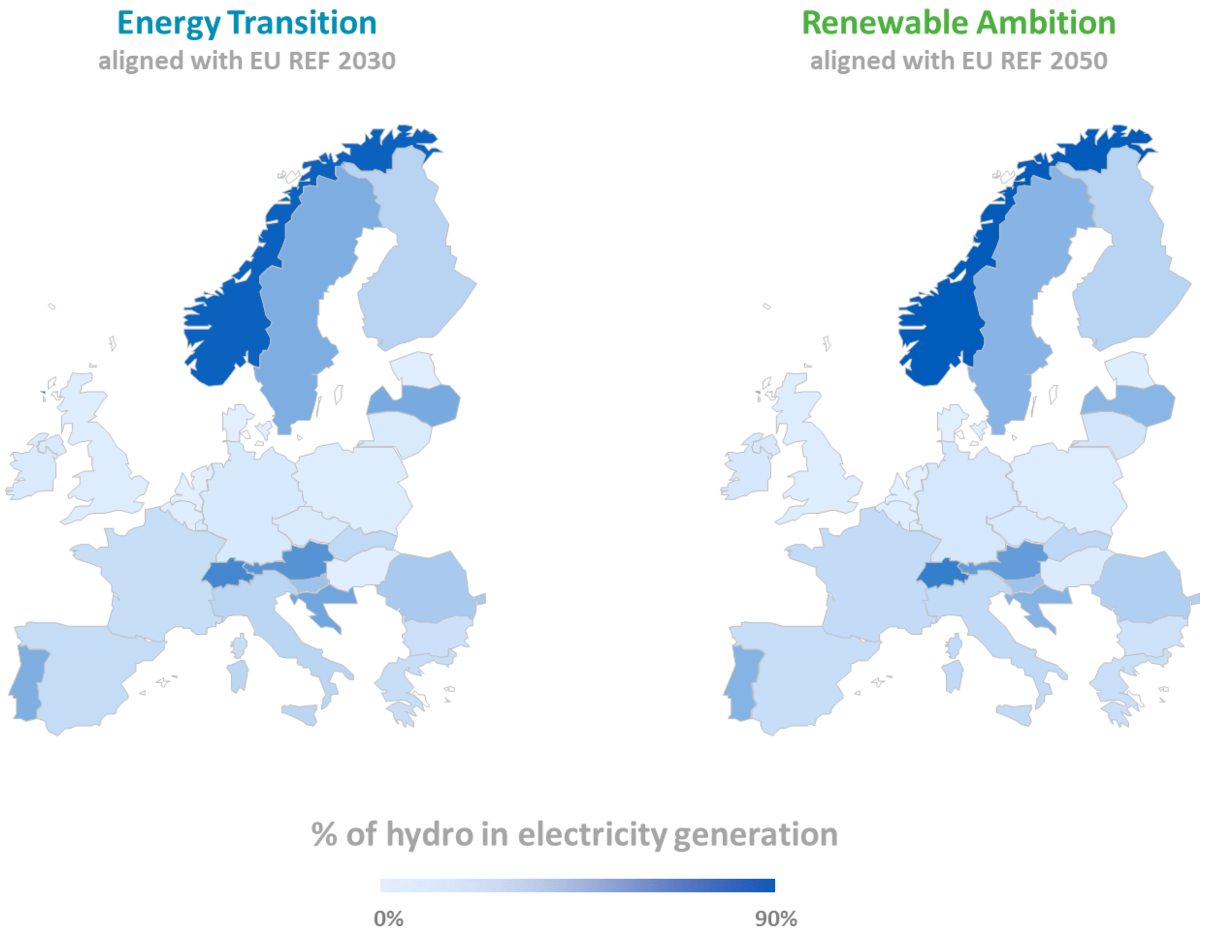


FIGURE 19: SHARE OF GENERATION FROM HYDROELECTRICITY FOR ENERGY TRANSITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2030 (LEFT) AND RENEWABLE AMBITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2050 (RIGHT)

3.3.1.4 WIND

The installed capacity of wind is increasing by 44% between the two scenarios **Energy Transition** and **Renewable Ambition.** The wind production represents 17% in **Energy Transition** and close to a quarter of the generation in **Renewable Ambition**. Wind turbines are developing only to the extent that market permits, as the support schemes are phased out. The generation is increasing through the development of new sites as well as through RES retrofitting. Where new plants are replacing older plants, the turbines are more efficient and have higher load hours.

In **Energy Transition**, the share of wind generation is upwards of 17% for 10 countries: Denmark, Ireland, Portugal, Greece, Belgium, Spain, the United Kingdom, Germany, The Netherlands, and Romania (see Figure 20). In **Renewable Ambition**, the share reaches upwards of 26% for 10 countries: Denmark, Ireland, Estonia, Spain, Greece, Portugal, Germany, Belgium, France and the United Kingdom.

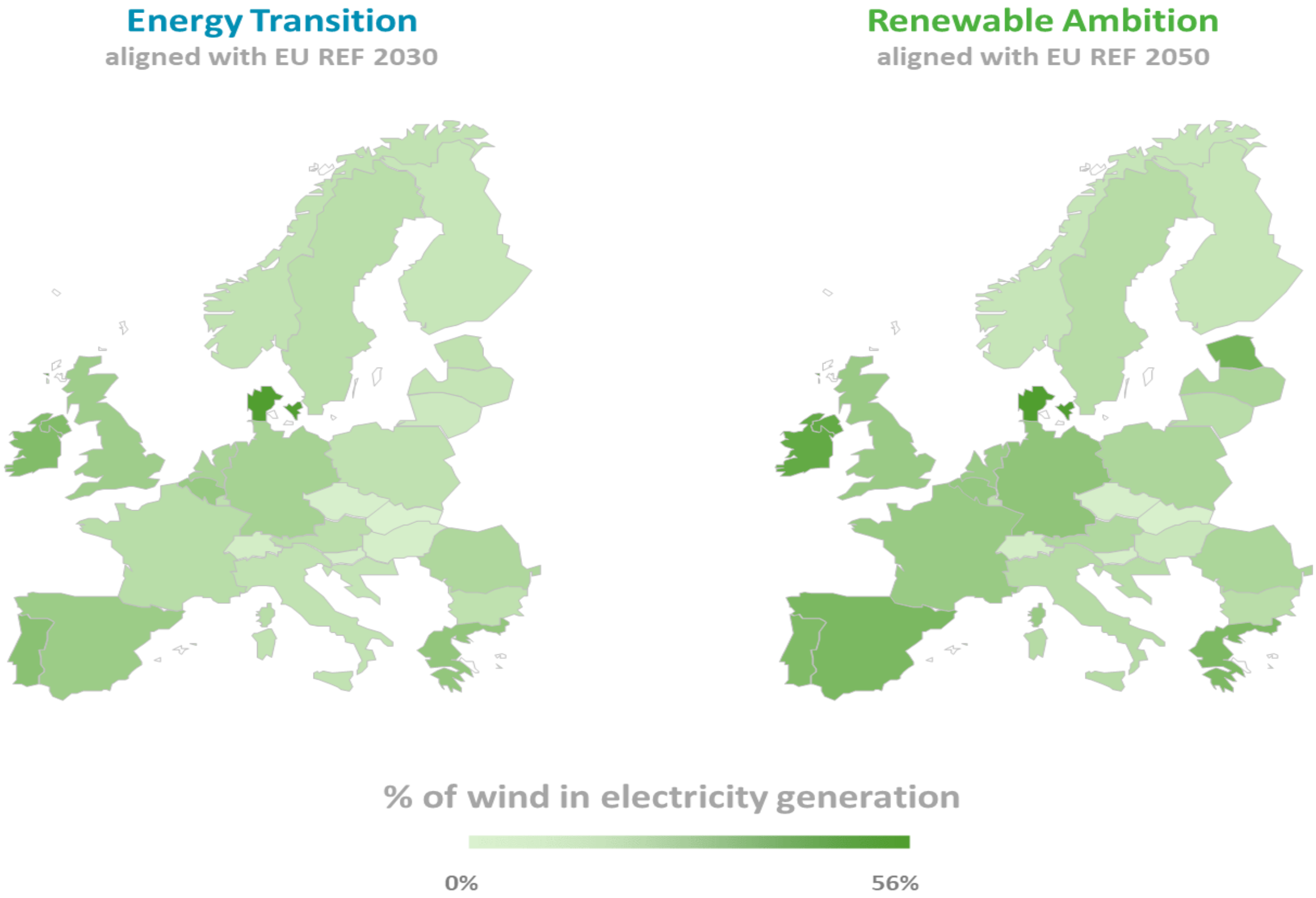


FIGURE 20: SHARE OF GENERATION FROM WIND FOR ENERGY TRANSITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2030 (LEFT) AND RENEWABLE AMBITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2050 (RIGHT)

3.3.1.5 SOLAR PV

The installed capacity of solar differs by 63% between **Energy Transition** and **Renewable Ambition**, with the higher installed capacity occurring in the **Renewable Ambition** scenario. Solar generation is contributing to 7% of the total annual energy production in **Energy Transition** and 10% in **Renewable Ambition**, with large discrepancies between Northern and Southern countries. Whereas the development of solar was first pushed by sharp drops in prices of solar modules combined with support schemes, the differences in the development of solar between **Energy Transition** and **Renewable Ambition** is a result only of market mechanisms as support schemes are phased out.

For both **Energy Transition** and **Renewable Ambition** the share of solar generation is highest in the countries located on the South of Europe, with the exception of Germany (see Figure 21). The 10 countries with the highest share of solar are, in alphabetical order: Croatia, Cyprus, France, Germany, Greece, Italy, Malta, Portugal, Spain, and Switzerland. In **Renewable Ambition**, these countries have upwards of 11% of solar generation in their power system, with Spain and Greece reaching a share of about 30%. The share in Portugal remains at 14%, despite its Southern location, as the share of hydroelectricity is very large.

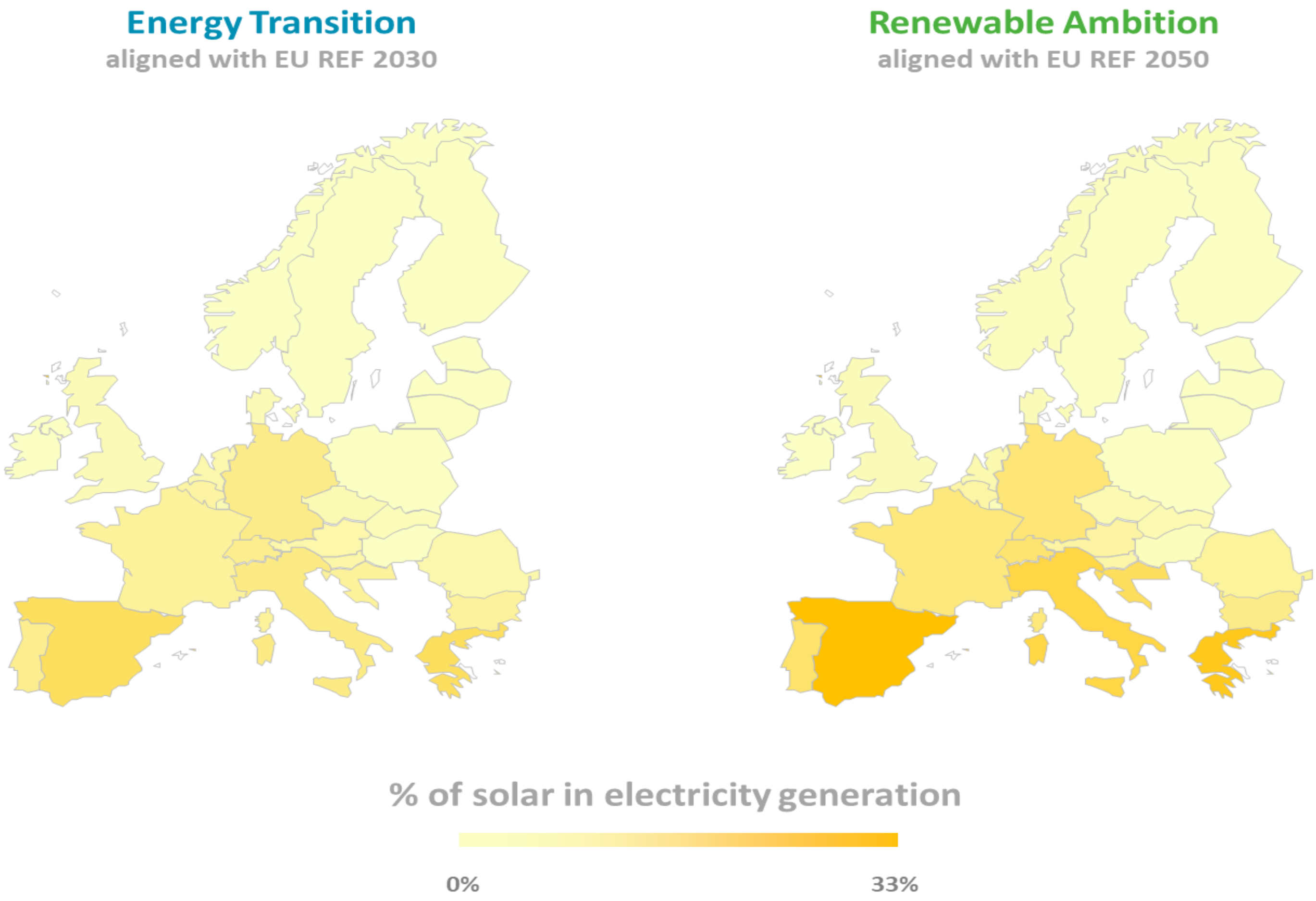


FIGURE 21: SHARE OF GENERATION FROM SOLAR FOR ENERGY TRANSITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2030 (LEFT) AND RENEWABLE AMBITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2050 (RIGHT)

3.3.1.6 BIOMASS

Biomass production and waste combustion increase between the **Energy Transition** scenario and the **Renewable Ambition** scenario from 8% to 10%. A small number of plants are pure biomass plants but the majority of biomass plants are co-firing plants. Like hydro production, biomass is a renewable energy whose generation can be optimized and controlled. In Energy Transition, the 10 countries having the highest share of biomass generation are Denmark, Finland, the United Kingdom, The Netherlands, Sweden, Latvia, Estonia, Germany, Italy, and Poland, with a share higher than 6% (see Figure 22). That share reaches roughly 22% for Denmark and Finland. Switzerland has a share of biomass in **Energy Transition** of 5% and of 15% in **Renewable Ambition**, coming in 5th position. In **Renewable Ambition**, the list is similar to **Energy Transition** with the addition of Switzerland.

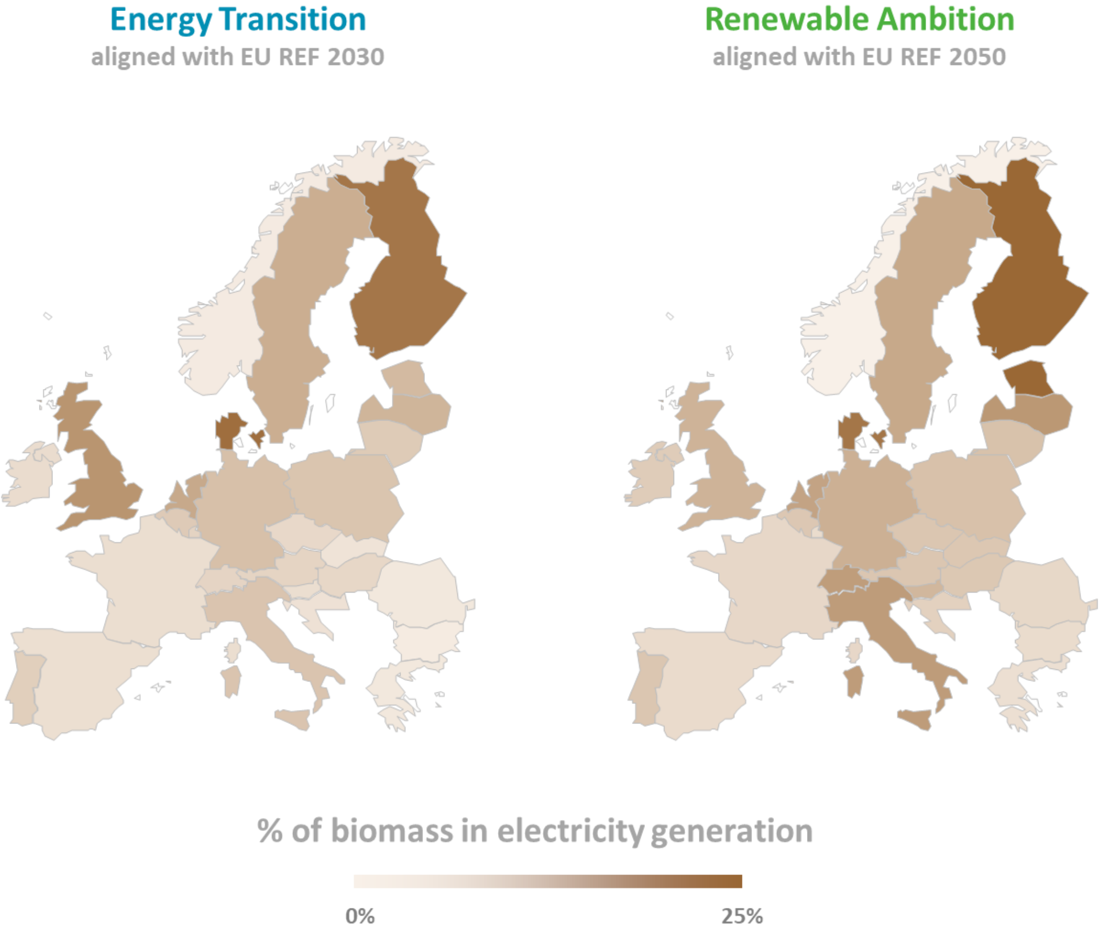


FIGURE 22: SHARE OF GENERATION FROM BIOMASS FOR ENERGY TRANSITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2030 (LEFT) AND RENEWABLE AMBITION ALIGNED WITH THE EU REFERENCE SCENARIO FOR 2050 (RIGHT)

3.3.1.7 GEOTHERMAL ELECTRICITY PRODUCTION

The share of geothermal plants remains very small in the production mix for both scenarios, reaching roughly 0.4% in **Renewable Ambition**.

4. EU-SYSFLEX NEWORK SENSITIVITIES - NORDIC POWER SYSTEM

It should be noted that while the EU-SysFlex Scenarios have been developed with the Nordic countries in all considerations, the EDF CONTINENTAL model, due to the scale of the model, models the Nordic power system with one node per country. Thus, in order to supplement and complement the scenarios developed and modelled in the EDF Continental model, scenarios for the Nordic power system will be studied in more detail using the WILMAR joint market model. WILMAR is a unit commitment and economic dispatch model, which can take advantage of stochastic wind and solar power forecasts and simultaneously optimize resources for power, heat and reserve markets (Kiviluoma, Rinne, Helisto, & Azevado, 2014).

The geographical model region for the Nordic power system includes Sweden, Finland, Norway and Denmark and zonal resolution is used (9 zones as in Figure 23). Similar to Continental Europe, the EU-SysFlex Scenarios (**Energy Transition** and **Renewable Ambition**) for the Nordic system are built based on the EU Reference Scenarios 2016. In addition, a Network Sensitivity has been created in order to further stress the Nordic power system and to explore a potential situation in 2030 where there are much higher levels of Solar PV. This Network Sensitivity is called High Solar.

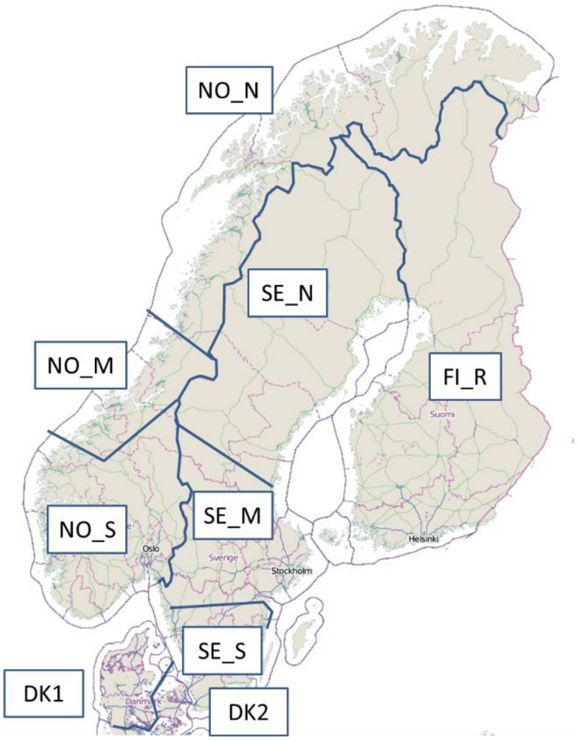


FIGURE 23: MODEL ZONES FOR THE NORDIC SYSTEM

Production cost simulations of the Nordic region will be linked with the CONTINENTAL model by matching hourly interconnector flows. These are exchanged on country level (as opposed to zonal resolution). An overview of the two Core EU-SysFlex Scenarios and the Network Sensitivity for the Nordic system (High Solar) is provided in Table 9.

TABLE 9: OVERVIEW OF THE EU-SYSFLEX SCENARIOS AND NETWORK SENSITIVITIES FOR NORDIC COUNTRIES

EU-SysFlex Scenario	Scenario Name	Climate Year	Interconnector Flows
Core Scenario 1	Energy Transition	2011	CONTINENTAL Model
Core Scenario 2	Renewable Ambition	2011	CONTINENTAL Model
Network Sensitivity 1	High Solar	2011	CONTINENTAL Model

4.1 ELECTRICITY DEMAND COMPONENTS

4.1.1 EU-SYSFLEX SCENARIOS

The EU-SysFlex Scenarios assume that electrification is a continuing trend. Assumptions regarding electrification of heat for the Nordic system are aligned, as much as possible, with the Continental European Scenarios, discussed above. However, in the Nordic model heating is understood as district heat, and electric heating is not explicitly considered.

Demand response (DR) is an important source of flexibility in Nordic countries because of the popularity of electric heating and the presence of energy intensive industry such as pulp and steel mills. DR capacities in the Nordic countries are tailored to align with the EU-SysFlex Scenarios.

The same penetration of electric vehicles as identified in Table 8, above, for the two EU-SysFlex Scenarios is assumed.

4.1.2 NORDIC POWER SYSTEM - HIGH SOLAR NETWORK SENSITIVITY

Electric heat pumps already have some significance in district heat (DH) production in Sweden and Finland. In 2017 the district heat production by heat pumps in Finland was 2.4 TWh, some 7.2 % of the total sales. In Sweden heat pumps in district heating produced some 4.6 TWh (Statistics Sweden, 2017). According to the Nordic energy technology perspectives 2016 (International Energy Agency; Nordic Council of Ministers, 2016), heat pumps in Nordic countries will produce some 10 TWh, which will increase to 60 TWh by 2050. The assumed installed capacities of heat pumps in the Nordic system are illustrated in Figure 24.

The same penetration of Electric Vehicles as for the EU-SysFlex scenario, **Energy Transition** (see Table 8), based on the TYNDP Distributed Generation 2030 scenario, was assumed for all of the countries in the Nordic system (ENTSO-E, 2018).

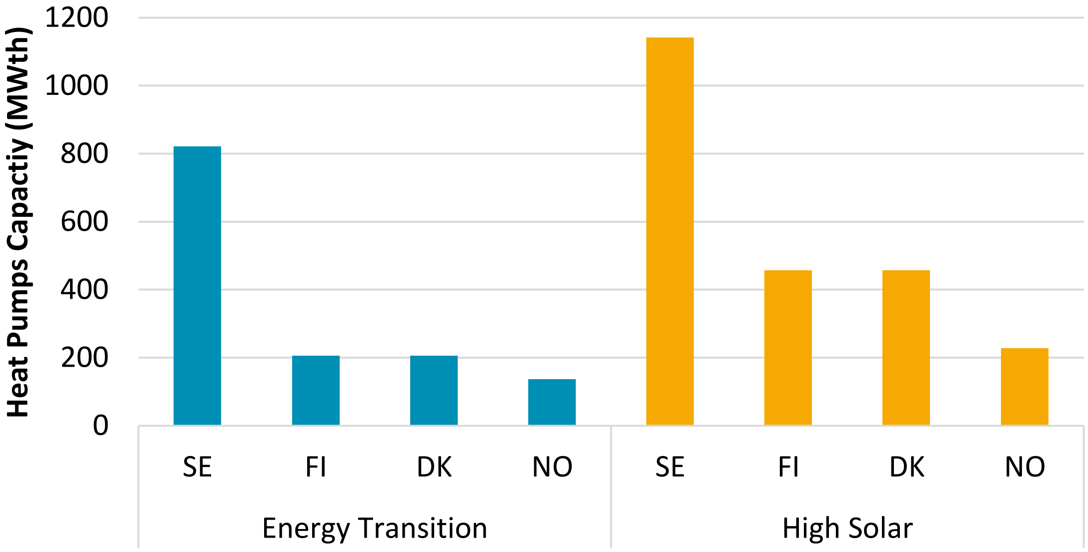


FIGURE 24: LARGE-SCALE HEAT PUMP PENETRATION IN ENERGY TRANSITION AND HIGH SOLAR NETWORK SENSITIVITY

4.2 ELECTRICITY SUPPLY

4.2.1 EU-SYSFLEX SCENARIOS

As mentioned previously, in the EU-SysFlex Scenarios, **Energy Transition** and **Renewable Ambition**, electricity supply assumptions are based on the EU Reference scenario 2016 for 2030 and 2050. For the Nordic power system, thermal plants capacities are aligned with the EU Reference Scenarios. VRE plants the energy produced listed in the Reference scenario are converted to plant capacities. For Norway, which is not included in the reference scenario, TYNDP EUCO2030 scenario was utilized as the source of power plant capacities for the EU-SysFlex Scenario Energy Transition (ENTSO-E, 2018).

The geographical resolution for the unit commitment and economic dispatch (UCED) simulation for the Nordic region is the market bidding zone, or in case of southern Norway and northern Sweden a group of bidding zones. In addition, more than one aggregated district heating networks was defined within some bidding zones. Therefore the country-level plant capacities have to be further divided into these smaller regions. The distribution used in TYNDP EUCO2030 scenario was utilized for division of the capacity for thermal, wind and solar plants, as shown in Figure 25. Power-to-heat plants were distributed according to the demand of district heat in each bidding zone and heat network. Figure 26 shows the resulting capacity mix.

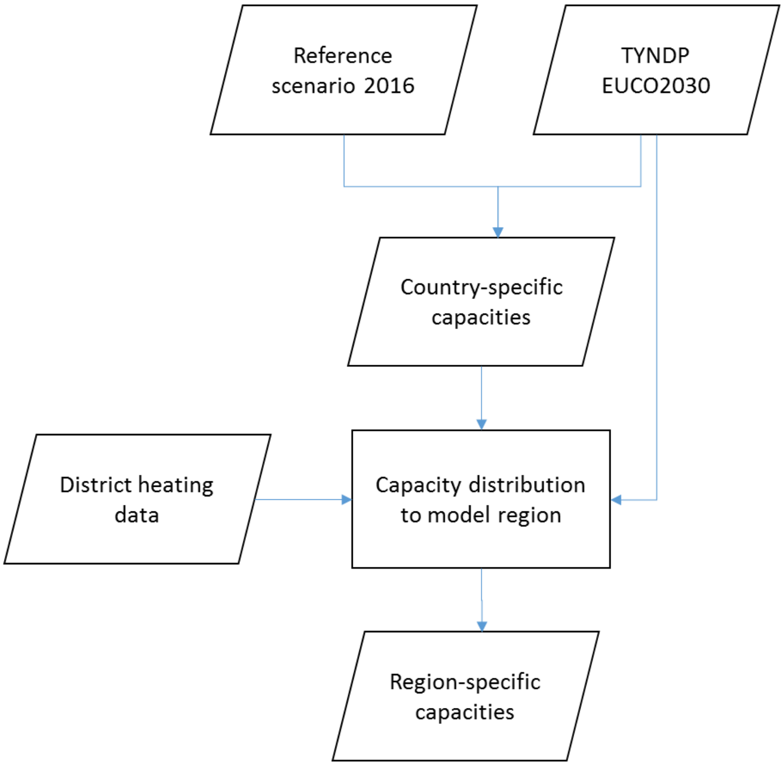


FIGURE 25: CAPACITY CALCULATION PROCESS IN ENERGY TRANSITION

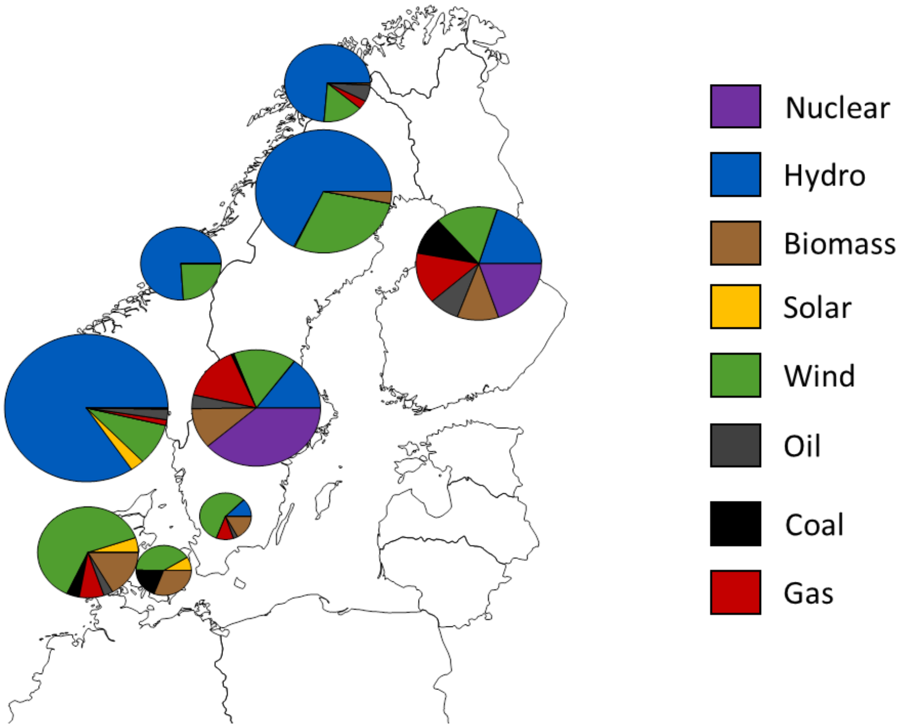


FIGURE 26: GENERATION CAPACITY MIX BY MODEL ZONE FOR THE NORDIC COUNTRIES IN THE ENERGY TRANSITION SCENARIO

The conversion process from the source data to plant portfolio in UCED simulation required some additional decisions. The EU Reference scenario 2016 or TYNDP scenarios are not very specific on the type of the production units. For example, EU Reference scenario gives the total amount of CHP plants per country but does not specify their fuel or technology. It was assumed that biomass-fired plants are always CHP plants unless their specified capacity exceeds the specified CHP capacity. Gas-fired plants, given their large capacity in the scenarios, were allocated to either combined cycle gas turbine with combined heat and power (CCGT-CHP), combined cycle gas turbine (CCGT) or open cycle gas turbine (OCGT) plants. Solids-fired plants were allocated to hard coal (condensing or CHP) and peat fired (CHP) plants. The biomass and waste category was assumed to include wood fuels, municipal solid waste and black liquor.

A similar capacity allocation process was done for the **Renewable Ambition** scenario. The main differences in electricity supply in the two scenarios were the greatly decreased capacity of solids-fired plants and greatly increased capacity of nuclear and gas-fired plants. Figure 27 shows the generation capacity per country in the **Energy Transition** and **Renewable Ambition** scenarios.

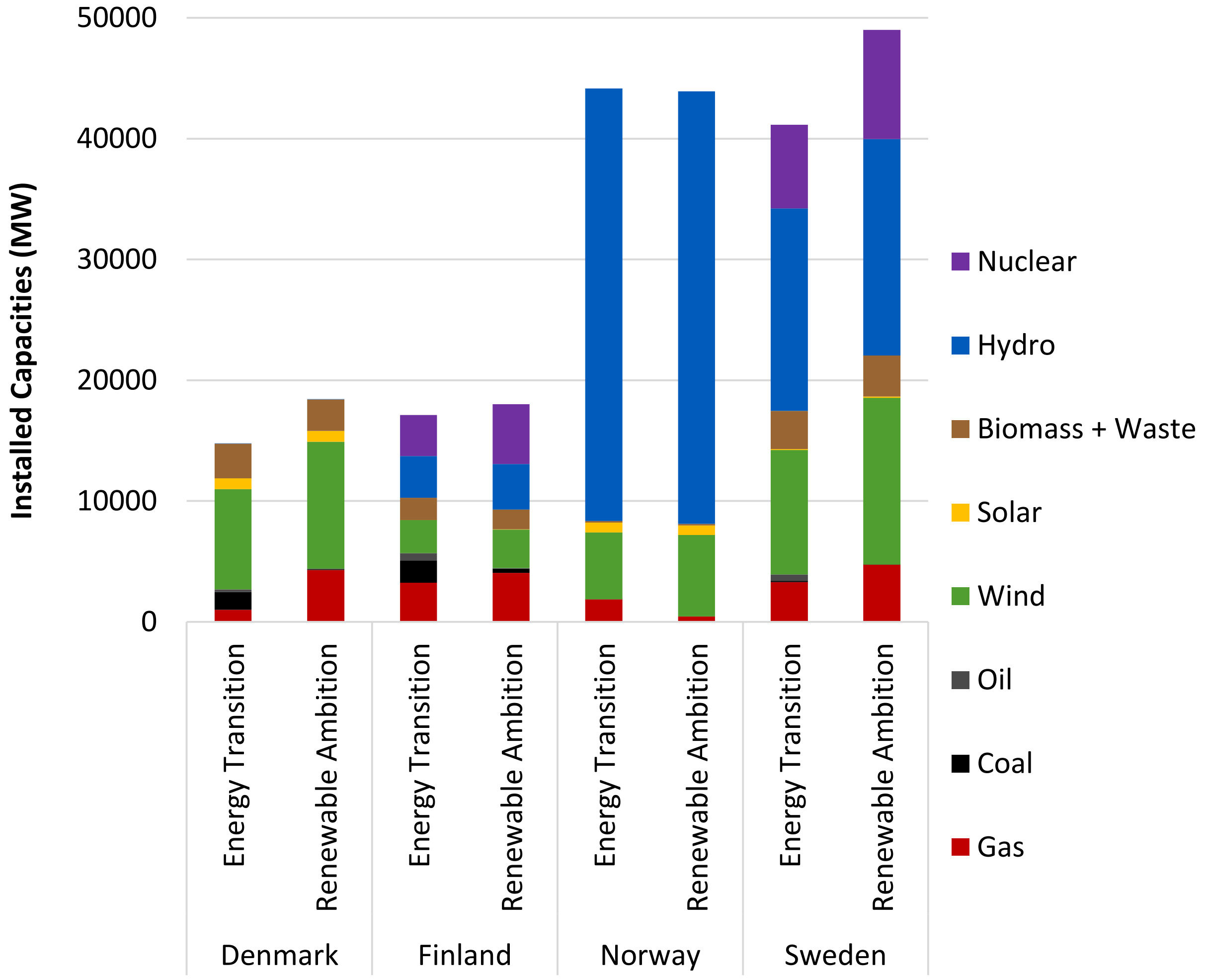


FIGURE 27: GENERATION CAPACITY MIX FOR NORDIC COUNTRIES FOR BOTH ENERGY TRANSITION AND RENEWABLE AMBITION

4.2.2 NORDIC POWER SYSTEM HIGH SOLAR NETWORK SENSITIVITY

Several parameters may be adjusted to explore the possible situations where problems may appear in the power system operation. The solar PV generating capacity in Sweden and Finland remains on low level for the Core Scenarios. In reality, these capacities have already been exceeded. For example, in the end of 2018 total of 100–150 MW PV is expected in Finland. Much higher solar PV capacities have been specified in the TYNDP scenarios. A "High Solar" scenario was thus formed where solar PV capacities were updated from the TYNDP DG2030 scenario (ENTSO-E, 2018). Significant uncertainty lies upon the possible nuclear capacity, which according to the EU Reference Scenario remains roughly the same in Sweden and significantly increases in Finland by 2050. Nuclear capacity was aligned with the assumed installed capacity in the **Energy Transition** scenario, which means that in Finland the Hanhikivi 1 plant will not be built (see Figure 28) and in Sweden shutdowns in Ringhals and Oskarshamn plants continue. Wind power capacity was set to align with the maximum of installed capacities in the Renewable Ambition Scenario and TYNDP scenarios for 2030. The installed capacities of different electricity generating technologies are shown in Figure 29.

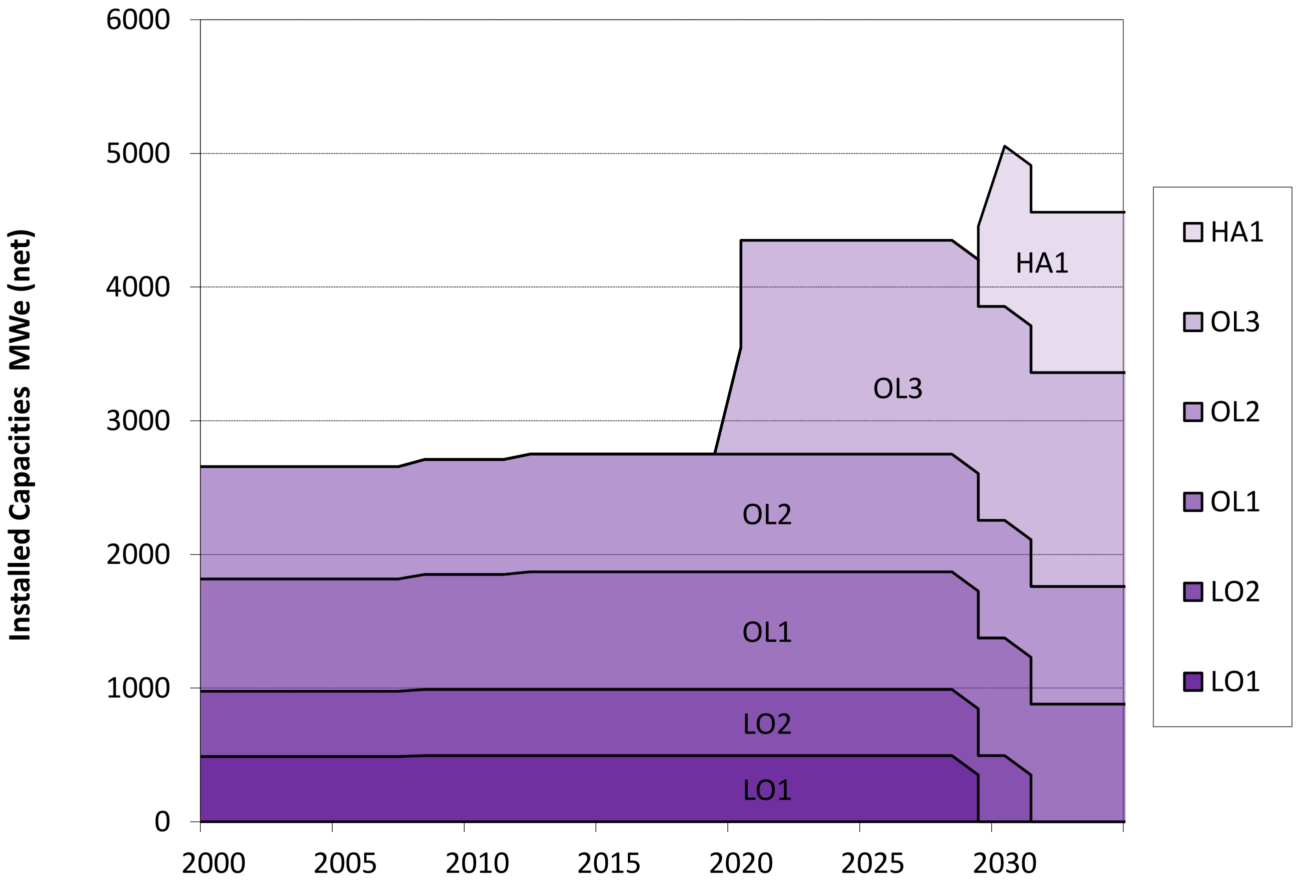


FIGURE 28: POSSIBLE DEVELOPMENT OF NUCLEAR CAPACITY IN FINLAND (LEHTILÄ, HONKATUKIA, & KOLJONEN, 2014). INDIVIDUAL REACTORS ARE SHOWN IN DIFFERENT COLORS

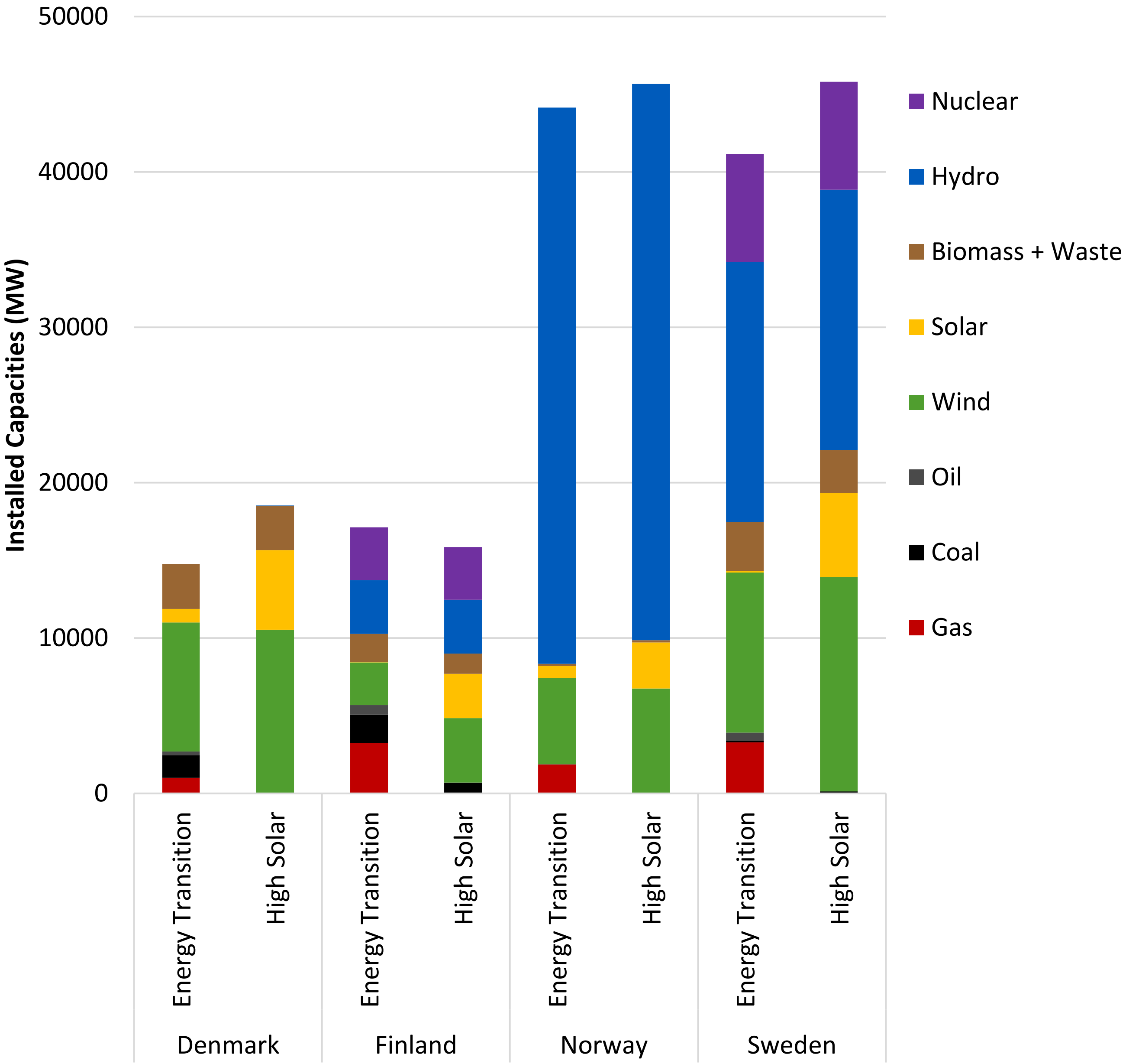


FIGURE 29 : GENERATION CAPACITY MIX FOR NORDIC COUNTRIES IN THE HIGH SOLAR NETWORK SENSITIVITY COMPARED WITH THE ENERGY TRANSITION SCENARIO

In terms of produced energy (Figure 30) the largest differences between the different scenarios are in nuclear power and to lesser extent in wind power and solar power. In Sweden and Denmark VRE has a clear effect on the full-load hours of biomass-fired plants. The use of fossil fuels is marginal in all scenarios.

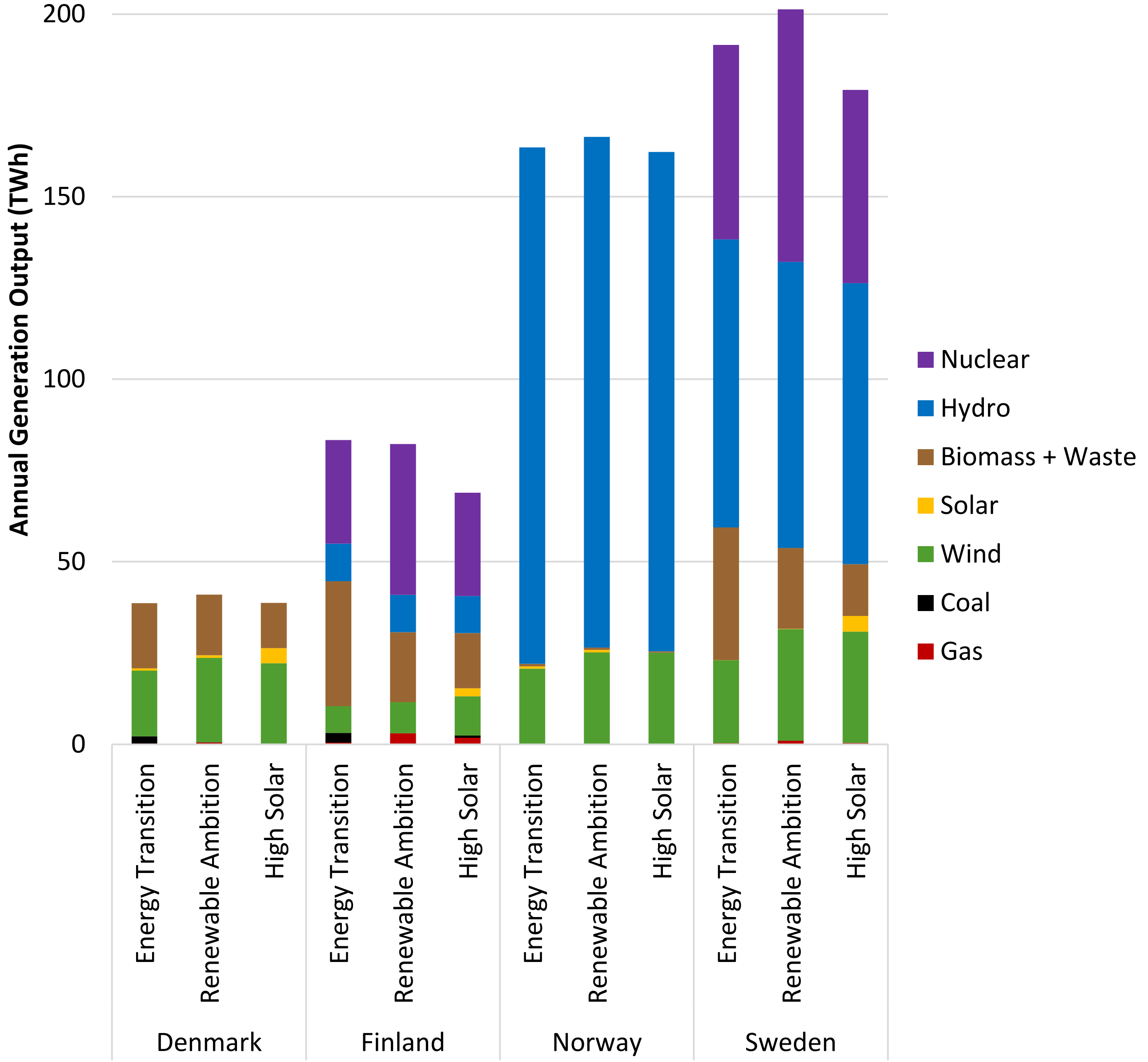


FIGURE 30: ANNUAL GENERATION OUTPUT BY FUEL TYPE FOR NORDIC COUNTRIES IN ALL SCENARIOS FROM THE NORDIC SYSTEM SIMULATION.

4.2.3 VARIABLE RENEWABLE ENERGY CAPACITY FACTOR TIME SERIES

The EMHIRES datasets (Gonzalez Aparicio, et al., 2016) were used as the hourly capacity factor time series for solar and wind power generation, similarly as in the Continental European case. However, as the Nordic system was modelled with bidding zone resolution, the datasets with higher spatial resolution were used. This causes a likely mismatch with the country-level time series used in the Continental European case, given that the distribution of VRE capacity is now a degree of freedom. Additional steps had to be taken to ensure that VRE production is equal for both Continental European and Nordic simulation. The primary solution is to modify the total production so that it matches the production calculated with the country-level series. This could take place in relation to the production on each bidding zone:

$$p'_{i,t} = p_{i,t} \frac{CP_t}{\sum_i C_i p_{i,t}} \tag{1}$$

Here i refers to the bidding zone (or group of bidding zones), $p_{i,t}$ is the original bidding zone level production time series, $p'_{i,t}$ is the updated , P_t is the country-level production time series, C_i is the bidding zone level capacity, and C is the country-level capacity. The drawback of this method is that if P_t strongly correlates with one of the $p_{i,t}$ series, situations where production takes place mainly on other bidding zones disappear from the updated series. Another solution would be to let the production series in the Continental European case and Nordic case differ and directly modify the interconnector flow time series. Notice that when energy matching is used, the bidding zone capacities C_i do not sum up to the country-level capacity. Instead the total energy relation (2) must hold:

$$\sum_i \sum_t C_i p_{i,t} = \sum_t CP_t \tag{2}$$

5. EU-SYSFLEX NETWORK SENSITIVITIES – SUB-NETWORK OF THE EUROPEAN POWER SYSTEM

The dynamic and voltage stability of a sub-network of the Continental European power system is being examined in detail as part of WP2. This sub-network will include a detailed network model of the Polish power system, and many surrounding countries including Germany, Austria, Czech Republic, Slovakia and Hungary. In conjunction with the EU-SysFlex scenarios, two Network Sensitivities have been developed – **Going Green** and **Distributed Renewables** (Table 10). These Network Sensitivities further increase the RES-E penetration in Poland to even more ambitious levels than those in the two Core Scenarios. The result is an increase in the level of non-synchronous generation and additional stresses on this sub-network of Europe. The investigated Network Sensitivities involve higher capacities of intermittent RES and different sizes of RES power plants. In Going Green, the RES is primarily connected to the transmission system, while in **Distributed Renewables** the RES is primarily connected to the distribution system.

As with all the Network Sensitivities, the generation mixes for the Network Sensitivities were chosen in a way that significantly stresses the system and yet still can be considered realistic. The capacities chosen in these sensitivities have the same aggregate behaviour on energy output, while having two different dynamic behaviours on the grid due to their connection points. Additionally, less strict requirements apply for units connecting at low voltage levels according to Network Code on Requirements for Generators (European Commission, 2016). This will be examined further during the simulations on these Network Sensitivities.

This region of Europe was chosen for further analysis for two reasons. The first reason is that there are ready availability of detailed grid models of this area, which will ease creation of detailed network models for the Core Scenarios and Network Sensitivities. For additional details on the development of the network models, the reader is directed to the EU-SysFlex D2.3 (EU-SysFlex, 2018). The second reason is that this region is characterised by significant diversity in the generation mix which will enable the observation of the impacts of high penetration of variable renewable generation on different portfolios and different systems.

Austria has vast hydro generation resources, which is an important resource to counterbalance effects of intermittent RES while Germany is experiencing rapid development of intermittent RES, in conjunction with significant nuclear generation phase-out. Poland traditionally was coal-dominated and now is moderately introducing more RES. Historically this has mostly been wind generation and co-firing power plants. However, in the scenarios and Network Sensitivities it is projected that solar PV will play an increasingly important role. The Czech Republic has a relatively large share of nuclear generation along with ambitions to increase level of nuclear generation and RES generation is dominated by Solar PV. Hungary is predominantly an energy importer with significant nuclear generation capacities.

TABLE 10: OVERVIEW OF THE SCENARIOS AND NETWORK SENSITIVITIES FOR CONTINENTAL EUROPE

EU-SysFlex Scenario	Scenario Name	Climate Year	Interconnector Flows
Core Scenario 1	Energy Transition	2011	CONTINENTAL Model
Core Scenario 2	Renewable Ambition	2011	CONTINENTAL Model
Network Sensitivity 1	Going Green	2011	CONTINENTAL Model
Network Sensitivity 2	Distributed Renewables	2011	CONTINENTAL Model

5.1 ELECTRICITY DEMAND COMPONENTS

The Network Sensitivities have the same assumptions concerning demand as the Core Scenarios as uncertainty concerning demand historically was much lower than the uncertainty about generation mix. The possibility of additional flexibilities on the demand side is not taken into account as the goal of Network Sensitivities is to stress the network while such additional flexibilities are part of solution that is being developed in EU-SysFlex Project.

5.2 ELECTRICITY SUPPLY

The **Going Green** Network Sensitivity has increased capacity of variable renewable generation (see Table 11). The wind capacity is increased from 10.4 GW in **Energy Transition** and from 18.9 GW in **Renewable Ambition** to 19.86 GW in **Going Green**. Solar PV capacity increased from 0.099 GW in **Energy Transition** and from 0.35 GW in **Renewable Ambition** to 3.26 GW. In the **Distributed Renewables** Network Sensitivity the overall generation mix is the same as in **Going Green**; however the modelled system consists of more units of lower capacities connected at a lower voltage level. A breakdown of the installed capacities by fuel type for Poland is illustrated in Figure 31 and Figure 32. Additional detail can be found in the Annex to this report.

For the studies of the Continental Europe sub-network, further sensitivity analysis will be carried out in the following way:

- **Going Green** – Sensitivity analysis will be carried out on the inertia constants outside Polish power system. This sensitivity analysis will simulate further increases in non-synchronous generation in all CE countries beyond Poland.

- **Distributed Renewables** – Sensitivity analysis will be carried out on equivalent impedances connecting the Continental Europe sub-network to other countries, as well as the EHV to distribution system equivalent impedances located in Germany, Austria, Czech Republic, Slovakia and Hungary. This sensitivity analysis will simulate further increases in non-synchronous generation within these countries, as well as simulating where these generators are connected in Germany, Austria, Czech Republic, Slovakia and Hungary, i.e. the transmission system or the distribution system.

Further information on the specific modelling techniques used to create these equivalents can be found in EU-SysFlex Deliverable 2.3 (EU-SysFlex, 2018).

TABLE 11: COMPARISON OF THE WIND AND SOLAR CAPACITIES AND THE DISTRIBUTION BETWEEEN HIGH AND LOW VOLTAGE NETWORKS IN THE POLISH SCENARIOS AND NETWORK SENSITIVITIES

	EU-SysFlex Core Scenarios		**Network Sensitivities of the Sub-Network of the European Power System**	
	Energy Transition	**Renewable Ambition**	**Going Green**	**Distributed Renewables**
Wind	10 339 MW	18 877 MW	19 860 MW	19 860 MW
Solar PV	99 MW	350 MW	3 260 MW	3 260 MW
of which connected above 110 KV	~83%	~83%	~83%	~16%
of which connected below 110 KV	~17%	~17%	~17%	~84%

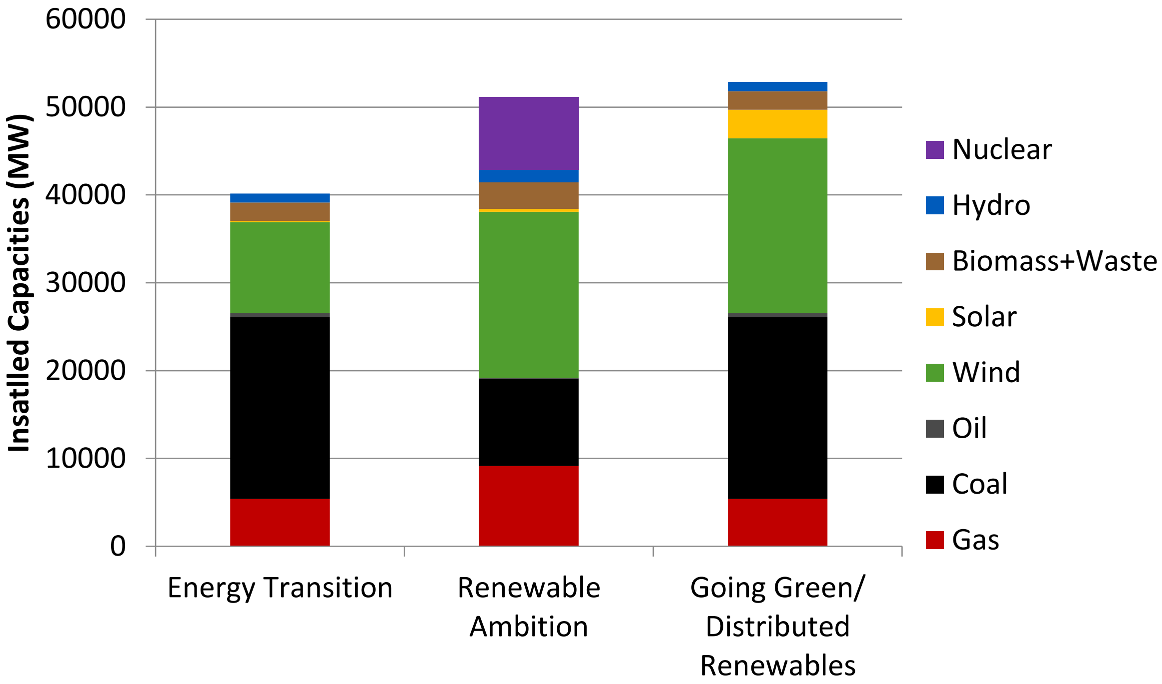


FIGURE 31: INSTALLED CAPACITIES FOR POLAND FOR THE TWO CORE SCENARIOS (ENERGY TRANSITION AND RENEWABLE AMBITION) AND THE TWO NETWORK SENSITIVITIES (GOING GREEN AND DISTRIBUTED RENEWABLES)

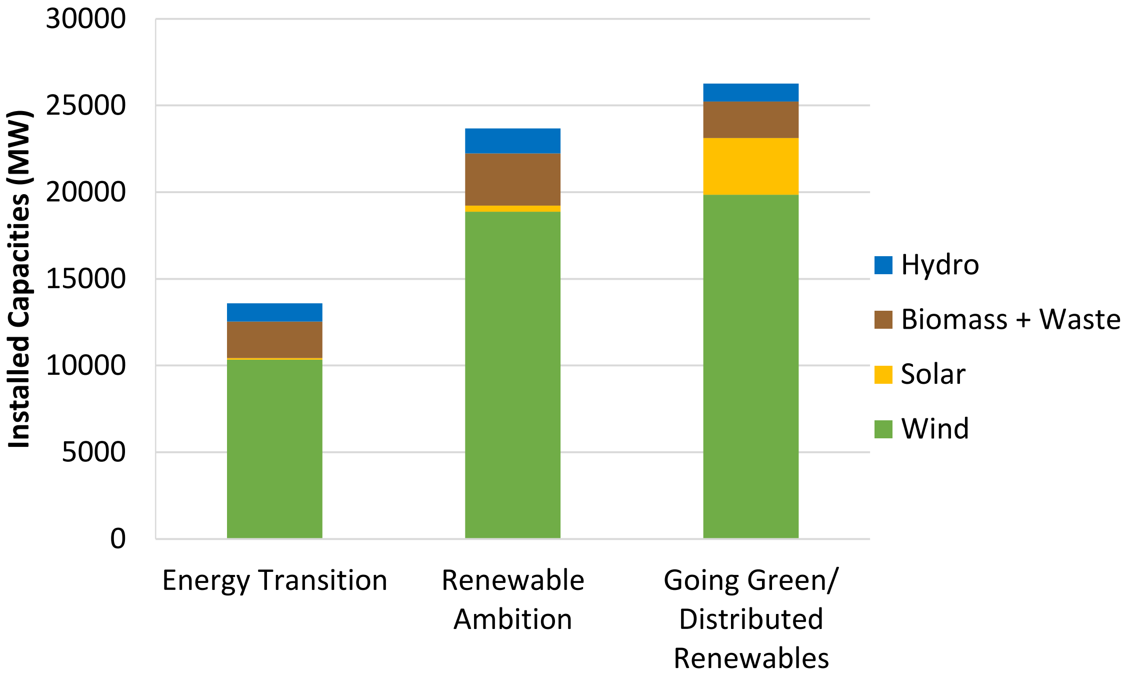


FIGURE 32: COMPARISON BETWEEN INSTALLED CAPACITIES OF RES-E IN POLAND IN THE DIFFERENT SCENARIOS

6. EU-SYSFLEX NETWORK SENSITIVITIES – IRELAND AND NORTHERN IRELAND

A detailed dynamic model of the Ireland and Northern Ireland power system has been developed as part of Task 2.3 to examine the frequency, dynamic, voltage and angular stability of the system at times of instantaneous non-synchronous RES-E penetration reaching close to 100% (EU-SysFlex, 2018). In order to carry out this analysis, additional Network Sensitivities of the Ireland and Northern Ireland power system are developed to be used in conjunction with the two EU-SysFlex scenarios.

In order to create the two EU-SysFlex scenarios from the EU Reference Scenario 2016 for the Ireland and Northern Ireland power system, the work completed for the Tomorrow's Energy Scenarios 2017 (EirGrid, 2017), is leveraged. The Tomorrow's Energy Scenarios (TES) 2017 outlines four scenarios for Ireland from 2020 – 2040. Each scenario has its own specific storyline based on potential economic, energy policy, and technical as well as consumer behaviour developments.

- **Slow Change -** The economy experiences very slow growth. Investment in new renewable generation is only in established, low risk technologies. Due to poor economic growth, new technologies that could increase the use of renewable generation at household and large scale levels are not adopted. Overall there is little change in the way electricity is generated when compared to today. Domestic consumers and commercial users are also avoiding risk and uncertainty. The only source of demand growth is the connection of new data centres but the level of investment slows down significantly after 2025.
- **Steady Evolution -** Renewable electricity generation maintains a steady pace of growth. This is due to steady improvements in the economy and in the technologies which generate electricity. New consumer technologies help to increase energy efficiency in homes and businesses.
- **Low Carbon Living** - The economy enjoys high economic growth. This encourages the creation and rollout of new technologies for low carbon electricity generation. A strong public demand to reduce greenhouse gas emissions, in addition to high carbon prices and incentives for renewables, creates a high level of renewable generation on the grid.
- **Consumer Action** - A strong economy leads to high levels of consumer spending ability. The public want to reduce greenhouse gas emissions. Electricity consumers enthusiastically limit their energy use and generate their own energy. This results in a large number of community led energy projects and a rapid adoption of electric vehicles and heat pumps in the home.

As the goal of the EU-SysFlex project is to examine systems with very high levels of renewable generation, Slow Change is not assessed as part of the EU-SysFlex project. **Steady Evolution**, **Low Carbon Living**, and **Consumer Action** are chosen to become Network Sensitivities for Ireland.

It should be noted that TES 2017 were developed for the Ireland power system only. Thus, there is currently no energy scenarios developed for Northern Ireland. Similarly, there are no direct EU Reference Scenarios 2016 for Northern Ireland only as it is considered as part of the UK generation and demand portfolios. Consequently, it was necessary to create a series of scenarios for Northern Ireland for the EU-SysFlex project. In order to do so data was taken from relevant TYNDP 2018 scenarios (ENTSO-E, 2018). Table 12 maps each of the scenarios used from TES 2017 to the relevant TYNDP 2018 scenarios. These corresponding TYNDP 2018 portfolios are used to create the equivalent Network Sensitivities for Northern Ireland.

TABLE 12: MAPPING OF THE TOMORROW'S ENERGY SCENARIOS WITH THE TYNDP 2018 SCENARIOS

TES 2017 Scenario		TYNDP 2018 Scenario
Steady Evolution 2030	↔	Sustainable Transition 2030
Consumer Action 2030	↔	Distributed Generation 2030
Low Carbon Living 2030	↔	Sustainable Transition 2030

The Core Scenarios and Network Sensitivities have been used to created production cost models in PLEXOS[2]. PLEXOS is a widely utilised tool for UCED problems, both within industry and in academia. The algorithm in PLEXOS determines the least cost manner in which to schedule generation to meet demand for each hour of the simulation, whilst being subject to a number of operating constraints. EirGrid & SONI have created five UCED models for the Ireland and Northern Ireland power system in PLEXOS. These five models correspond to two Core Scenarios (**Energy Transition** and **Renewable Ambition**) as well as the three Network Sensitivities (**Steady Evolution**, **Low Carbon Living**, and **Consumer Action**).

TABLE 13: OVERVIEW OF THE CORE SCENARIOS AND NETWORK SENSITIVITIES FOR IRELAND AND NORTHERN IRELAND

EU-SysFlex Scenario	Scenario Name	Climate Year	Interconnector Flows
Core Scenario 1	Energy Transition	2011	CONTINENTAL Model
Core Scenario 2	Renewable Ambition	2011	CONTINENTAL Model
Network Sensitivity 1	Steady Evolution	2015	TYNDP Model
Network Sensitivity 2	Consumer Action	2015	TYNDP Model
Network Sensitivity 3	Low Carbon Living	2015	TYNDP Model

---

[2] While every effort has been made to ensure alignment between all the models between partners, there may be slight discrepancies in the production outputs. In the case of the scenarios as represented in the EirGrid and SONI PLEXOS models and by EDF in the CONTINENTAL models, these discrepancies arise due to the use of different optimisation solvers and due to the fact that detailed models of the Ireland and Northern Ireland power system, with many unique technical parameters, are being utilised in PLEXOS. These discrepancies are minimal and do not have any significant impacts to overall RES-E levels or production outputs.

Across the three Network Sensitivities for EU-SysFlex, the installed renewable generation capacities for the Ireland and Northern Ireland power system varies between 9,000 MW and 15,000 MW by 2030. Thus, the Network Sensitivities for Ireland and Northern Ireland project much higher installed capacities of renewable generation than the EU Reference Scenario 2016 scenarios, which have approximately 6,500 MW and 8,300 MW of renewable generation for **Energy Transition** and **Renewable Ambition**, respectively. Consequently, the more ambitious scenarios from the Tomorrow's Energy Scenarios 2017 for Ireland plus the tailored TYNDP 2018 scenarios for Northern Ireland are the ideal sensitivities to utilise in order to stress the power system of Ireland and Northern Ireland and to identify technical scarcities.

The electrical demand and supply assumptions in the Network Sensitivities for Ireland and Northern Ireland are discussed in more detail in the following sections.

6.1 ELECTRICITY DEMAND COMPONENTS

In the Network Sensitivities for the Ireland and Northern Ireland power system, future demand growth is mainly being driven by large energy users, such as data centres connecting onto the grid. In addition, the adoption of electric vehicles and heat pumps contributes to future project demand growth. Today, data centres account for less than 2% of Ireland's total electricity demand. This is predicted to increase to as much as 36% by 2030 in some Network Sensitivities (EirGrid, 2017). One feature of data centres is that they tend to have a flat, predictable demand profile. This means they use the same amount of electricity throughout the day and night. It is projected that data centre installations will account for over 75% of new demand growth (EirGrid, 2017). The largest data centre demand growth is in the **Low Carbon Living** Network Sensitivity, while the largest adoption of electric vehicles and heat pumps occurs in the **Consumer Action** Network Sensitivity (EirGrid, 2017). This can be seen in Table 14. Breakthroughs in server technology may mean electricity demand from data centres may decrease in the future. These possible energy efficiencies have been factored into the Network Sensitivities.

A method to potentially reduce emissions in the heating sector is to electrify heating. If the electricity used to generate heat comes from renewable sources, this will reduce overall emissions. Reducing overall heating demand through energy efficiency will also help to meet targets. Storage heaters can be used to store heat which is typically generated by electricity at night. The stored heat is then released throughout the day. Heat networks, or district heating, which uses the emitted heat from power generation, may also be a possibility in large cities and towns. Community owned combined heat and power (CHP) plants may become more widespread in Ireland in the future. This situation has been considered to be likely in **Consumer Action**, where consumers are invested in generating their own energy and lowering their carbon footprint.

Another technology which can be used to electrify heating supply and lower emissions is a heat pump. Heat pumps are used for space heating and cooling, as well as water heating. There are a number of different types of heat pumps which can use water, air or the ground as a source of heat. Heat pumps are considered in the Network Sensitivities to be the primary method by which heating electrifies in the future (see Table 14).

The Network Sensitivities are predicting a relatively slow uptake of pure electric vehicles until 2025-2030. It is likely that hybrid vehicles will act as a transition between fossil fuel vehicles and electric vehicles. From 2025 onwards, improvements to battery technology and decreasing capital costs of electric vehicles are expected to significantly increase the level of electric vehicle uptake.

The increasing number of smart devices in the home, combined with the rollout of smart meters, will lead to an increased level of 'peak shifting'. This movement may occur in response to price signals to use electricity at less expensive times. It is expected that these price signals will play an increasing role in reducing the Total Electricity Requirement (TER) peak seen in the Network Sensitivities over time. It is likely that consumers will become more aware of their energy consumption in the future. Demand side management describes the situation where a consumer changes their energy consumption pattern due to a price signal. Domestic smart devices will enable consumers to 'shift' their electricity consumption from expensive tariff hours to cheaper tariff hours. This will result in lower transmission system peak demand and increased demand during the night.

Taking all of the above demand assumptions into account produces very distinct demand profiles for each of the scenarios and Network Sensitivities. This is illustrated using the load duration curves in Figure 33 as well as using a typical winter days load profile in Figure 34. It can be seen that demand profiles in the **Low Carbon Living** and **Consumer Action** Network Sensitivities are higher than in the Core Scenarios and the other Network Sensitivity (Figure 33), while there is also increased smart demand shifting assumed in **Low Carbon Living** and **Consumer Action**, which is evident from the flatter daily load profile in Figure 34.

TABLE 14: SUMMARY OF DEMAND BREAKDOWN FOR EACH OF THE SCENARIOS AND SENSITIVITIES FOR IRELAND AND NORTHERN IRELAND

	EU-SysFlex Core Scenarios		Ireland and Northern Ireland System Network Sensitivities		
Demand	**Energy Transition**	**Renewable Ambition**	**Steady Evolution**	**Low Carbon Living**	**Consumer Action**
Total Data Centre Capacity	Data not available. Assumed to be implicitly included in the demand profile		1 100 MVA	1 950 MVA	1 675 MVA
EVs as a % of Total Fleet			11%	19%	25%
% of Households with heat pumps			10%	14%	17%
Total Demand	**41 TWh**	**47 TWh**	**48 TWh**	**59 TWh**	**58 TWh**

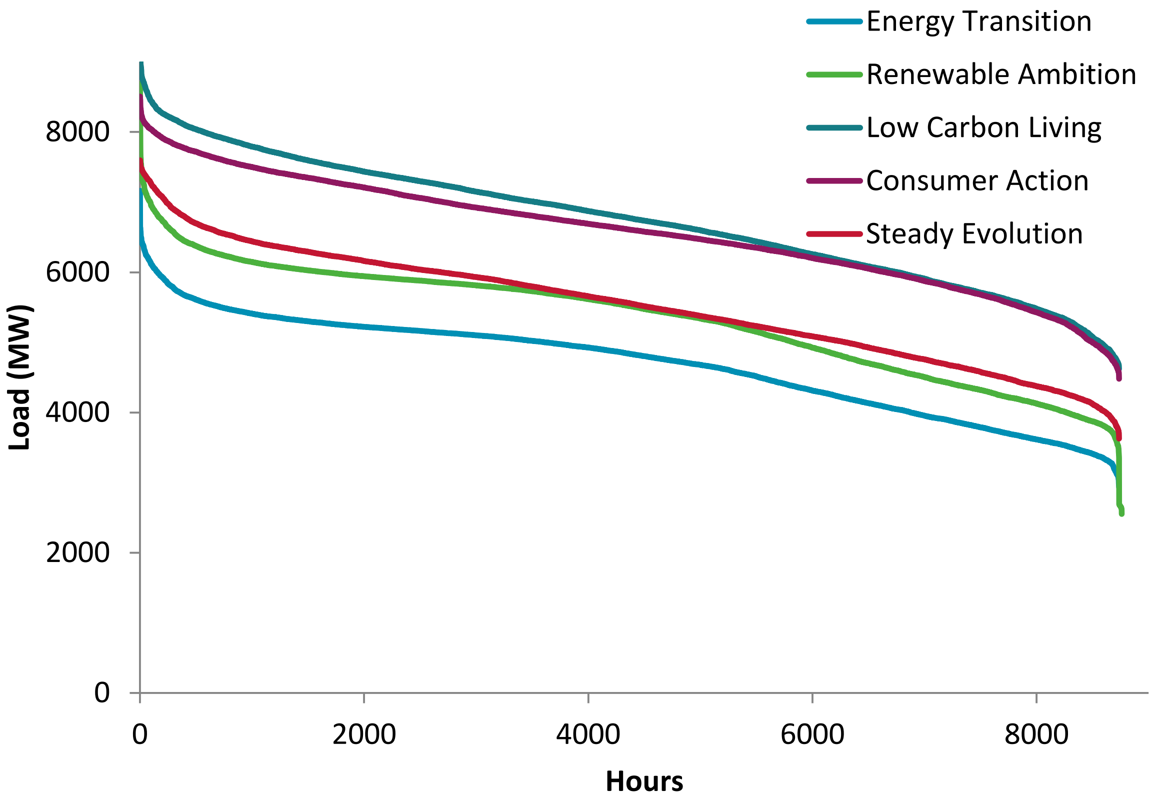


FIGURE 33: LOAD DURATION CURVES FOR THE FIVE IRELAND AND NORTHERN IRELAND SCENARIOS

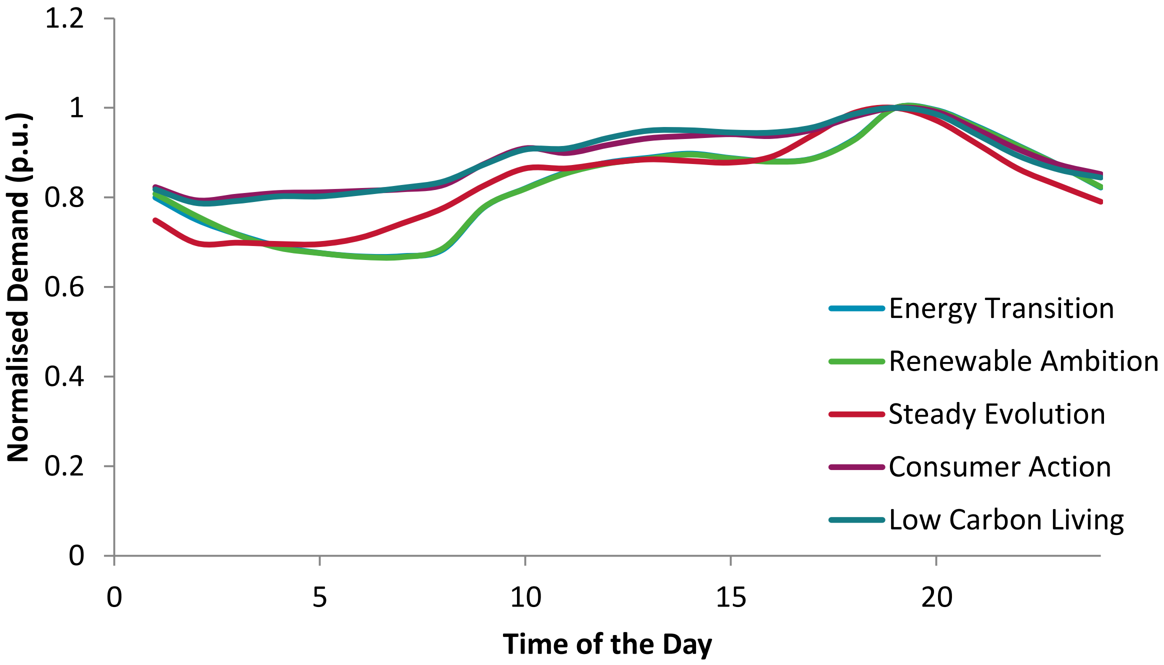


FIGURE 34: A NORMALISED DAILY DEMAND PROFILE FOR THE WINTER PERIOD FOR THE FIVE SCENARIOS FOR THE IRELAND AND NORTHERN IRELAND POWER

6.2 ELECTRICITY SUPPLY

An overview of the installed generating capacity for the Ireland and Northern Ireland power system for the two Core Scenarios and three Network Sensitivities is illustrated in Figure 35. The resulting generation production from these portfolios is given in Figure 36.

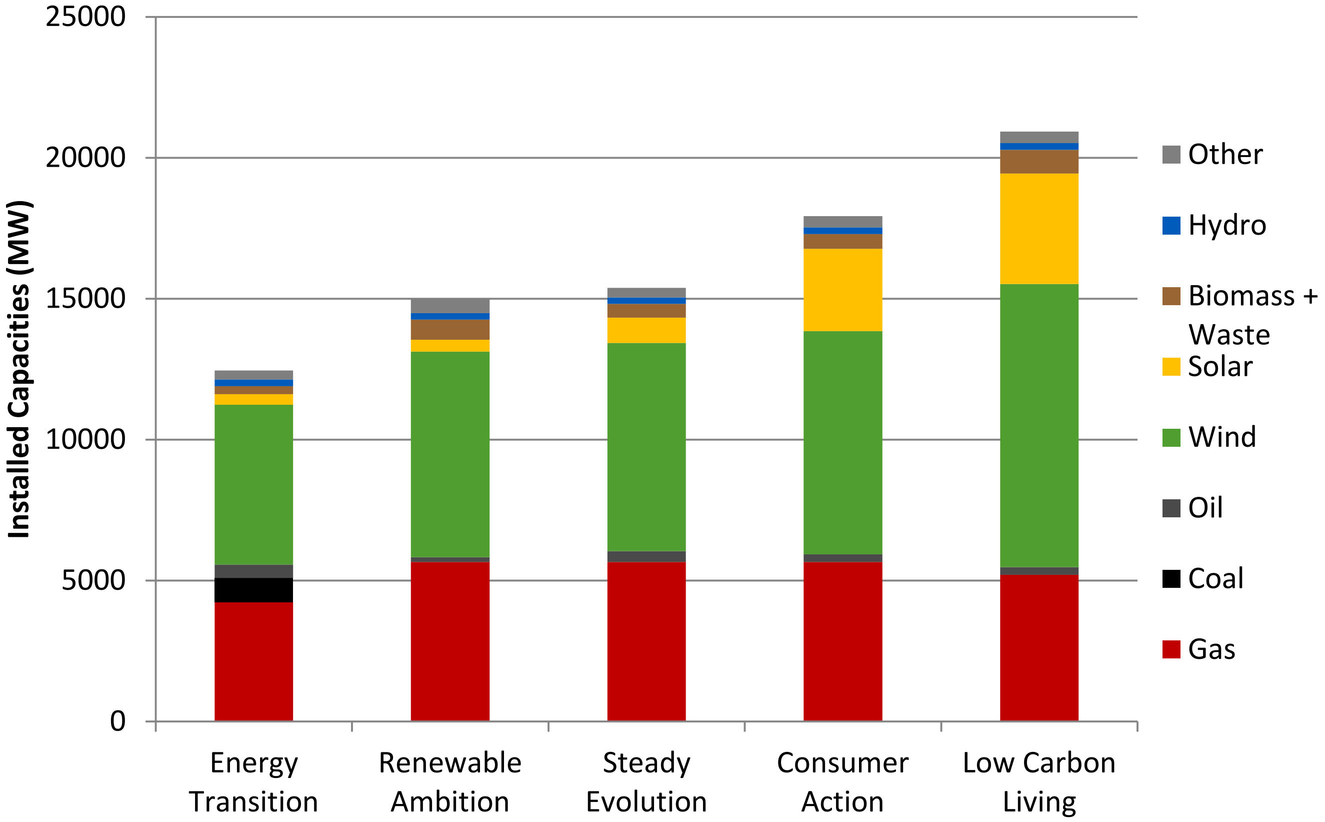


FIGURE 35: INSTALLED CAPACITIES FOR THE IRELAND AND NORTHERN IRELAND POWER SYSTEM

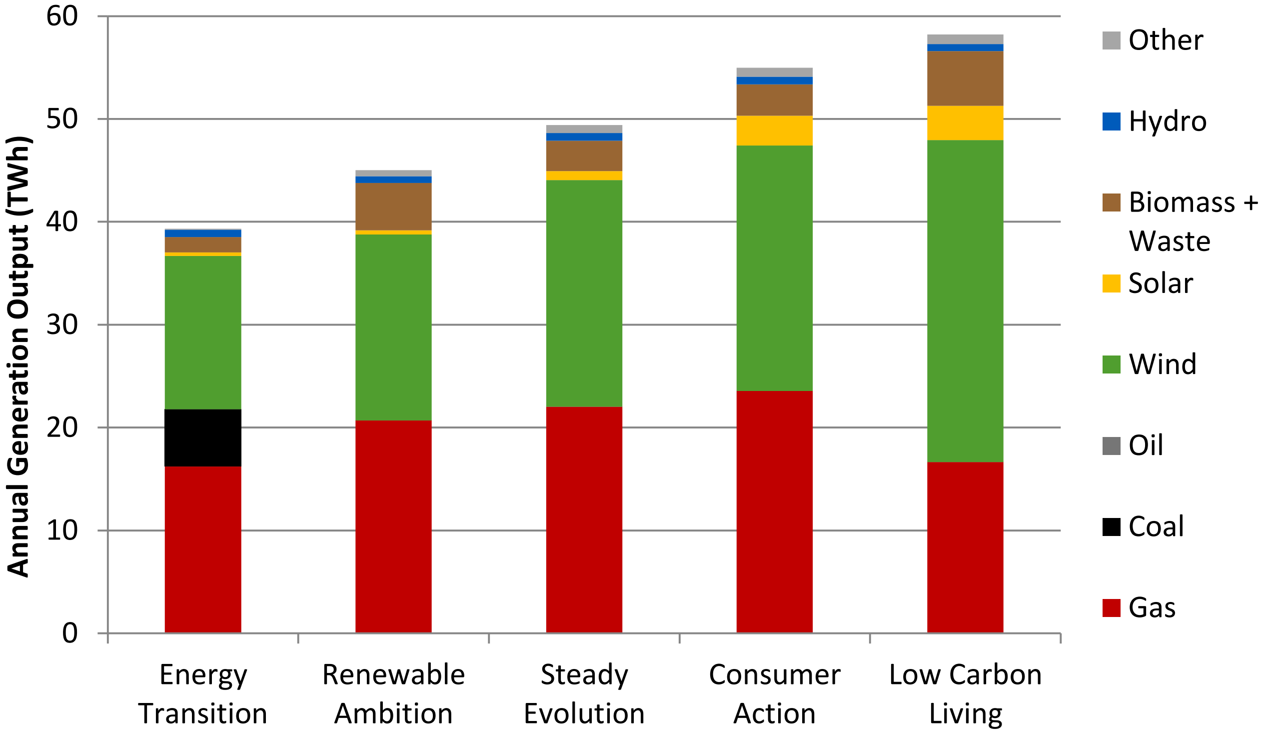


FIGURE 36: ANNUAL GENERATION OUTPUT BY FUEL TYPE FOR IRELAND AND NORTHERN IRELAND FOR THE CORE SCENARIOS AND NETWORK SENSITIVITIES

Additional detail can be found in the Annex to this report.

6.2.1 FOSSIL FUELS

6.2.1.1 COAL

Ireland's coal-fired generation has sufficient emissions abatement technology installed to run unhindered under current EU Emissions Directives. Future emissions directives may require further works to maintain running of coal-fired plants. All of the Network Sensitivities assume that coal generation has ceased in Ireland by 2030 and in one of the Network Sensitivities, **Low Carbon Living**, by 2025 (EirGrid, 2017). Similarly, in Northern Ireland coal generation is phased out by 2030 for all three Network Sensitivities. There are a number of possibilities for the future repowering of the coal generation units with gas, biomass, carbon capture and storage and other technologies being considered. For the purposes of the Network Sensitivities, it is assumed that gas is the fuel type chosen for the repowering of the coal plants in Ireland in the future.

6.2.1.2 GAS

Gas is widely considered to be the ‘cleanest’ fossil fuel with the lowest levels of carbon dioxide emitted per MWh of energy generated. In all three Network Sensitivities, many of Ireland’s older gas generation units on the power system will have retired by 2025 due to EU Emissions Directives. However, there is an assumption that new gas generators will be on the system between 2017 and 2040. In some of the network sensitivities, distillate oil units in Ireland retire over time but in other Network Sensitivities they convert to gas to reduce their emissions output. In the vast majority of the EU-SysFlex scenarios and Network Sensitivities, gas remains the predominate fossil fuel. This can clearly be seen in Figure 36.

6.2.1.3 OTHER FUELS

Peat has the highest carbon dioxide intensity of any fossil fuel. The cost competitiveness of running peat generation, relative to other fossil fuels will likely diminish as the price of carbon rises over time. A reduction in the carbon dioxide intensity of electricity generated from peat stations can be achieved by ‘co-firing’ biomass with peat. ‘Co-firing’ involves using two different fuels at the same time to output power. Peat generation has ceased in all the Network Sensitivities. In some Network Sensitivities it is replaced by biomass.

Distillate oil is primarily used for some of the peaking plants in Ireland. Multiple variations of these plants retiring or converting to gas in order to decarbonise is considered in the various network sensitivities.

Waste-to-energy power generation increases in capacity with the of two small waste-to energy plants before 2030. All the Ireland and Northern Ireland scenarios and Network Sensitivities assume that 50% of waste comes from renewable sources. This is based on historical figures available from existing waste-to-energy generators. This renewable content contributes to the overall renewable generation on the system.

6.2.2 RENEWABLE GENERATING TECHNOLOGIES

6.2.2.1 WIND

It is projected that continued development of onshore wind generation will be required to meet Ireland and Northern Ireland’s future decarbonisation targets in a cost effective way. Ireland has enormous potential for offshore energy developments. However, in Ireland and Northern Ireland, offshore wind is more costly to develop than onshore wind per MWh of energy. Although prices are dropping, it is still likely that subsidies will be required for its significant development off the coast of Ireland. It is also very likely Ireland will require some additional offshore wind generation to meet future decarbonisation targets as is reflected in the Network Sensitivities. This could act as the beginning of an offshore wind generation network which could be used to transmit power throughout Europe. It is likely that offshore generation networks will be crucial for Europe’s long term decarbonisation objectives. In Ireland, the installed wind capacity varies in the Network Sensitivities from 5.8 GW to 8.5 GW, while in Northern Ireland wind capacity is projected to reach upwards of 1.5 GW.

6.2.2.2 SOLAR PV

Ireland and Northern Ireland has a similar potential solar resource to that of many parts of Great Britain and Germany. Both of these countries have seen dramatic increases in the levels of solar generation connecting onto their systems in the past decade. However, in both situations, guaranteed feed-in-prices were made available for the generation of solar energy.

It is likely that decreasing capital costs, due to technology breakthroughs, will see large scale solar PV connecting to the system at an increasing rate from the mid-2020s without the need for a subsidy. For this reason, solar only sees marginal growth in Ireland in the **Steady Evolution** Network Sensitivity out to 2025. The **Low Carbon Living** Network Sensitivity sees a faster pace of growth, with the most economically viable solar sites developing faster due to the better economy (EirGrid, 2017). Solar generation is most likely to locate in the southern and eastern parts of the country as they have the most sun exposure. This would give an average capacity factor of 11%. Other areas of Ireland tend to have less sun exposure, giving average capacity factors of 8-10%. In Northern Ireland, the installed solar PV capacities range from 0.4 GW in **Steady Evolution** to 1.4 GW in **Low Carbon Living** and in **Consumer Action**. Consequently, the increase in solar PV capacity forms the majority of the renewable generation development.

Rooftop solar PV on households and businesses remains relatively expensive. It is unlikely large capacities will materialise until post-2025 unless the government incentivises it. It is likely that utility scale solar would need to develop first in order to develop rooftop solar PV in the absence of an incentive scheme. This would build up a skilled workforce and decrease the capital costs of rooftop solar PV. The **Consumer Action** Network Sensitivity has the highest level of rooftop solar PV capacity in 2030, as consumers take control of their own electricity supply. Widespread rooftop solar PV can have a large impact on the electricity demand which is ‘served’ by the transmission system. Power generated from rooftop solar PV can be consumed by the home or building, stored in a household battery for later use, or exported into the distribution grid. This can have an impact on the usage of the transmission grid.

6.2.2.3 BIOMASS

All of the Network Sensitivities show biomass generation increasing in capacity over the next 25 years. This includes some new generators, combined with an uptake in community led combined heat and power schemes. There is also a conversion of Ireland’s peat generation stations to biomass in some Network Sensitivities. As there is not sufficient biomass growth in Ireland and Northern Ireland to maintain the required quantity to fuel large capacities, the majority of the biomass fuel which Ireland requires may need to be imported.

6.2.2.4 HYDRO AND OCEAN

It is assumed that the current hydro generation stations will remain active throughout all the Network Sensitivities.

Ireland and Northern Ireland have a considerable potential for ocean generation. However, wave and tidal generation technology remains in its infancy and is very expensive to develop. Some developments are considered in our Network Sensitivities, with the largest capacity nearing 300 MW by 2040 in **Low Carbon Living** (EirGrid, 2017). It is assumed that the learnings taken from pilot projects improve the technology costs, and it begins to become commercially viable beyond 2030. It is likely ocean energy will have a larger role to play in Ireland’s decarbonisation later in this century. It may also benefit from possible connections to future offshore grid networks.

6.2.3 ENERGY STORAGE

Electricity storage can be used for a variety of system needs, for example energy arbitrage, provision of system services, or congestion management. Electricity storage at large scale levels has traditionally used pumped hydro energy storage (PHES). More recently, compressed air energy storage (CAES) has also seen growth across some European countries and in North America.

Battery energy storage (BES) has become more economically viable due to decreasing capital costs.. Large scale grid connected battery energy storage will likely connect along with renewables such as solar and wind to help manage variability. Household battery energy storage will likely connect with domestic solar PV to provide additional self-consumption for consumers. Two categories of battery storage have been considered. Large scale battery storage is considered to be battery banks installed in total capacities of 10 MW or greater. These units may be standalone units or else installed with transmission or distribution connected wind or solar PV farms. Small scale battery storage is considered to be either domestic household batteries or battery banks with total capacities of less than 10 MW on the distribution system.

As well as batteries, a 360 MW PHES station connects to the power system in the **Low Carbon Living** Network Sensitivity. This PHES plant is in addition to an already existing 292 MW PHES plant.

6.2.4 INTERCONNECTION

Ireland and Northern Ireland also have an existing interconnector tie which uses High Voltage Alternating Current (HVAC). The North South Interconnector is in the grid development process and would increase the total transfer capacity between Ireland and Northern Ireland to 1,100 MW. Ireland and Northern Ireland are currently interconnected to Great Britain through the East-West Interconnector (EWIC) and the Moyle Interconnector. EWIC has a capacity of 450 MW. Similarly, Moyle uses HVDC technology and has a capacity of 500 MW. Both the

Core scenarios and the Network Sensitivities consider interconnection to France in 2030. In addition, the Network Sensitivities consider an additional interconnector to Great Britain. The connection dates of the interconnectors vary depending on the scenario. It is assumed that the additional interconnector to Great Britain in the **Low Carbon Living** Network Sensitivity.

7. CONCLUSIONS

This report outlines the development process for scenarios and Network Sensitivities which will be used in the technical and market modelling analysis for the EU-SysFlex project. The outcome of this work is a set of coherent and transparent scenarios for the European power system, which are consistent with the aims and objectives of the EU-SysFlex project, and a number of Network Sensitivities which examine various sub-networks of the European power system in greater detail. The scenarios chosen for the EU-SysFlex project are a crucial starting point for the technical and market modelling analysis which is central to the project.

In developing scenarios for the EU-SysFlex project, two categories of scenarios were defined:

Core Scenarios – These are the central scenarios which will define the installed generation capacities by fuel type, demand, interconnection and storage portfolios to be used. These scenarios will be used to produce total annual energy demand as well as total annual energy production by source and fuel type. These scenarios will be used throughout the project for technical and production cost simulations on a European basis.

Network Sensitivities – These are sensitivities which examine various parts of the European network and will vary the capacities and locations of demand, generation, interconnection or storage in order to examine various scenarios in specific countries of the European power system. These sensitivities will be used to assess more specific technical scarcities in certain parts of the European system.

An initial investigation phase of the EU-SysFlex scenario development took place with a review of European scenario literature, starting in November 2017 to meet the February 2018 Milestone of the EU-SysFlex project, ‘MS1 – Agreement on Core Modelling Scenarios’. This literature review formed the starting point for the EU-SysFlex Scenarios. The review explored using data from the European Commission’s EU Reference Scenario 2016 and EUCO Policy Scenarios, and ENTSO-E Ten Year Network Development Plan (TYNDP) 2018 Scenarios. In addition, the e-highways2050 scenarios and EDF’s 60% RES-E (Electricity from Renewable Energy Sources) pan-European scenario were also investigated.

Following this assessment, it was determined that the EU Reference Scenarios 2016 would form the basis for the two core scenarios chosen for the EU-SysFlex project. The EU Reference Scenarios 2016 met the criteria defined for the EU-SysFlex scenario selection in that:

- They are consistent with the goals of the EU-SysFlex project (i.e. they have at least 50% RES-E for the European power system);
- They have a publicly available and complete dataset for each of the scenarios with individual EU28 country breakdowns;
- They incorporate the targets, policies and directives of the European Union;
- They are recently developed scenarios as they were published in 2016; and

- By using two of scenario years of the EU Reference Scenarios 2016, there is a direct and coherent relationship between the two Core Scenarios to allow for easy comparisons – with one of the scenarios being more ambitious than the other in terms of the scale of the renewables energy production.

The two chosen scenarios are based on the generation and demand portfolios for the European Commission's EU Reference Scenario 2016 for 2030 and 2050 respectively using various 2030 European network models for EU-SysFlex simulations. Information from the EU Reference Scenarios 2016 was supplemented with additional information from other sources for countries outside of the EU, and for obtaining information on profiles for EVs and Heat Pumps. This included information from the ENTSO-E TYNDP 2018 scenarios for Norway and Switzerland. For the purposes of the EU-SysFlex project, the two scenarios will be known as the **Energy Transition** scenario, which is based on the EU Reference Scenario 2016's demand and generation portfolio for 2030, and the **Renewable Ambition** scenario, which is based on the EU Reference Scenarios 2016's demand and generation portfolio for 2050.

The **Energy Transition** Scenario has a percentage of electricity from renewable energy sources (RES-E) with respect to overall demand of 52%, while the **Renewable Ambition** Scenario has a RES-E percentage of 66%. These RES-E figures are consistent with the goal of the EU-SysFlex scenarios in examining the European power system at very high levels of renewable energy. The fact that two different time horizon portfolios from the EU Reference Scenarios 2016 are used for different ambition levels in the EU-SysFlex core scenarios provides a distinct advantage in having two linked scenarios for the entire European system, and the sub-networks and power systems chosen for additional analysis. These core scenarios and Network Sensitivities will be used throughout all aspects of the EU-SysFlex project. The scenarios enable consistency across all modelling tasks in various EU-SysFlex Work Packages which will increase the ease of comparing different analysis across the project.

In addition to the percentage of RES-E in the two core scenarios, the percentage of variable non-synchronous renewable resources is of particular interest to the EU-SysFlex project. As highlighted in the EU-SysFlex D2.1 – State-of-the-Art Literature Review of System Scarcities at High Levels of Renewables, the challenges of integrating high levels of renewable generation are primarily seen at times of high non-synchronous generation penetration. Therefore, within the two core scenarios, the hours which have the highest levels of non-synchronous generation will be examined in detail through technical simulations to understand future system scarcities. Table 15 provides a summary of the renewable generation production, electricity demand and RES-E levels seen in for each European country in the two EU-SysFlex scenarios. Table 16 provides a summary of the carbon-free generation and non-synchronous variable renewable generation for each of the EU member states considered in the EU-SysFlex scenarios.

TABLE 15: PERCENTAGES OF RENEWABLE ENERGY PRODUCTION IN THE ENERGY TRANSITION AND RENEWABLE AMBITION SCENARIOS AS A PERCENTAGE OF DEMAND

	Energy Transition			Renewable Ambition		
Country	**RES production (TWh_e)**	**Demand (TWh_e)**	**%RES**	**RES production (TWh_e)**	**Demand (TWh_e)**	**%RES**
AT	62	73	85%	73	83	88%
BE	29	89	32%	41	108	37%
CH	45	61	74%	74	56	132%
CZ	9	66	14%	16	79	21%
DE	267	559	48%	385	580	66%
DK	29	36	80%	35	44	80%
ES	163	257	63%	282	291	97%
FI	43	84	51%	50	96	52%
FR	211	469	45%	362	548	66%
HU	3	39	8%	9	47	19%
IE	14	28	48%	21	34	63%
IT	148	314	47%	273	395	69%
LU	1	8	12%	2	12	14%
NL	50	116	43%	67	133	50%
NO	155	117	132%	160	110	145%
PL	40	168	24%	71	202	35%
PT	42	48	88%	50	51	98%
SE	113	144	78%	133	166	80%
SK	7	31	21%	10	34	31%
UK	176	356	49%	201	438	46%
Total	**1 607**	**3 063**	**52%**	**2 315**	**3 507**	**66%**

TABLE 16: CHARACTERISTICS OF THE EU-SYSFLEX SCENARIOS FOR THE 28 EU MEMBER STATES, SWITZERLAND AND NORWAY, FOR CARBON-FREE ELECTRICITY AND VARIABLE NON-SYNCHRONOUS RENEWABLE ENERGY (VRE) AS A PERCENTAGE OF ELECTRICITY PRODUCTION

	Energy Transition				Renewable Ambition			
Country	% carbon - free	% VRE	VRE of which		% carbon - free	% VRE	VRE of which	
			% Wind	% Solar			% Wind	% Solar
EU-28	**65**	**24**	**72**	**28**	**73**	**35**	**70**	**30**
AT	78	17	75	25	81	23	75	25
BE	40	32	83	17	41	33	84	16
BG	57	18	63	37	70	23	57	43
CH	94	13	26	74	100	18	27	73
CY	29	26	32	68	41	38	33	67
CZ	43	4	28	72	70	5	38	62
DE	44	31	68	32	60	43	70	30
DK	81	58	96	4	80	58	97	3
EE	21	11	100	0	67	42	100	0
ES	77	42	60	40	86	71	54	46
FI	77	8	100	0	91	8	100	0
FR	98	20	67	33	94	38	69	31
GR	57	46	63	37	78	66	58	42
HR	64	16	56	44	73	31	46	54
HU	90	2	90	10	77	9	85	15
IE	42	36	100	0	59	49	100	0
IT	46	21	49	51	65	36	41	59
LV	61	9	100	0	70	19	100	0
LT	81	6	93	7	82	14	97	3
LU	22	14	81	19	18	13	87	13
MT	13	13	-	100	22	20	13	87
NL	40	24	85	15	43	29	88	12
NO	97	10	100	-	99	12	96	4
PL	20	11	100	0	57	18	99	1
PT	87	41	79	21	96	52	71	29
RO	76	21	83	17	75	25	74	26
SE	93	13	100	0	94	14	100	0
SI	67	6	29	71	87	6	31	69
SK	94	2	4	96	84	4	23	77
UK	71	26	91	9	70	28	93	7

In addition to the **Energy Transition** and **Renewable Ambition** scenarios, various Network Sensitivities have been developed which seek to stress particular parts of the European network in order to examine further technical scarcities in greater detail. These Network Sensitivities are used to investigate more onerous or more ambitious generation and demand portfolios for specific areas and countries. The Network Sensitivities are focused on the areas of the European power system which will undergo increased analysis and simulations. Therefore, the areas which were primarily chosen for Network Sensitivities are the Ireland and Northern Ireland power system and a sub-network of the Continental European power system centralised around the Poland network. Additionally, a further sensitivity for the Nordic system has been developed.

The EU-SysFlex scenarios and Network Sensitivities are modelled using several different methods and software packages depending on the area being analysed. The Continental Europe system for the **Energy Transition** and **Renewable Ambition** scenarios is modelled using the EDF State-of-the-Art Unit Commitment software suite known as CONTINENTAL. This suite is an integrated electric generation and transmission market simulation system. It balances electricity supply and demand over the medium-term, on numerous scenarios reflecting the uncertainty, for a set of interconnected zones, minimising the overall production cost. The CONTINENTAL model is also used to set interconnector flows between various synchronous areas examined in other models.

To supplement and complement the EDF CONTINENTAL model for the Continental Europe system, the Nordic power system is studied in detail using the WILMAR joint market model. WILMAR is a unit commitment and economic dispatch model, which can take advantage of stochastic wind and solar power forecasts and simultaneously optimise resources for power, heat and reserve markets. WILMAR is used to model the **Energy Transition** and **Renewable Ambition** scenarios, as well as the Network Sensitivity for the Nordic system – **High Solar**. Production cost simulations of the Nordic region are linked with the CONTINENTAL model by matching hourly interconnector flows.

A sub-network of the Continental European power system will be examined in detail in WP2. This sub-network is focused around the Poland power system and the neighbouring countries. This sub-network will be tested using the **Energy Transition** and **Renewable Ambition** scenarios, along with two further Network Sensitivities – **Going Green** and **Distributed Renewables** – which examine the region with even higher levels of non-synchronous renewables compared to the **Renewable Ambition** scenario. The EDF CONTINENTAL model will be used to develop generation and demand profile snapshots for the two Network Sensitivities in Task 2.4.

Finally, the Ireland and Northern Ireland power system will utilise PLEXOS modelling software to generate production schedules for the Core Scenarios – **Energy Transition** and **Renewable Ambition** – and three further Network Sensitivities – **Steady Evolution**, **Low Carbon Living** and **Consumer Action**. The PLEXOS model of the Ireland and Northern Ireland power system is a sophisticated production cost model which allows the generation units to be modelled individually and detailed system and market constraints to be included and assessed. The Network Sensitivities developed for the Ireland and Northern Ireland system allow for even higher levels of renewable generation to be assessed in comparison to the **Renewable Ambition** scenario. The range of renewable generation installed across the power system in the five cases varies from 6,500 MW to 15,000 MW in 2030. A link is built between the Continental model and the PLEXOS model by matching hourly interconnector flows for the **Energy Transition** and the **Renewable Ambition** scenarios.

A summary of the scenarios and Network Sensitivities considered by all partners for further analysis is in Table 17.

TABLE 17: SUMMARY OF THE SCENARIOS AND NETWORKS SENSITIVITIES DEVELOPED FOR THE EU-SYSFLEX PROJECT

PARTNER	System considered	Core scenarios		Network Sensitivities		
EDF	Continental system	**Energy Transition**	**Renewable Ambition**	-	-	-
VTT	Nordic system	**Energy Transition**	**Renewable Ambition**	**High Solar**	-	-
PSE	Poland and neighbours	**Energy Transition**	**Renewable Ambition**	**Going Green**	**Distributed Renewables**	-
EirGrid & SONI	Ireland and Northern Ireland	**Energy Transition**	**Renewable Ambition**	**Steady Evolution**	**Consumer Action**	**Low Carbon Living**

The two Core Scenarios, **Energy Transition** and **Renewable Ambition**, and the various Network Sensitivities presented within this report will be used throughout the EU-SysFlex project. The technical models to be used within WP2 have been developed in Task 2.3 in consideration of these scenarios. Similarly, production cost models have been developed for the two Core scenarios and the Network Sensitivities. The dispatches from these models will be used in co-ordination with the technical models developed in Task 2.3. This will form the starting point for the technical simulations which will identify the future system scarcities of the European power system within Task 2.4. These scenarios will also be used in Task 2.5 to enable a valuation of future System Services to help solve the scarcities found within Task 2.4.

In addition to their use in WP2, the Core Scenarios and Network Sensitives will also be used in other Work Packages of the EU-SysFlex project. This includes WP3, which will define new System Services and market designs for the future European power system, and WP10 which will outline a roadmap for adapting the learnings of the entire EU-SysFlex project to enable the European power system to reach the ambitious levels of renewable generation found in the **Renewable Ambition** scenario. As demonstrated, the Core Scenarios and Network Sensitivities documented in this report are central to the EU-SysFlex project.

8. COPYRIGHT

Changes in this document will be notified and approved by the PMB. This document will be approved by the PMB.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under EC-GA No 773505.

BIBLIOGRAPHY

Burtin, A., & Silva, V. (2015). *Technical and Economic Analysis of the European Electricity System with 60% RES.* EDF Research and Development Division. Retrieved from http://www.energypost.eu/wp-content/uploads/2015/06/EDF-study-for-download-on-EP.pdf

E3MLab & IIASA. (2016). *Technical report on Member State results of the EUCO policy.* doi:https://ec.europa.eu/energy/sites/ener/files/documents/20170125_-_technical_report_on_euco_scenarios_primes_corrected.pdf

e-Highway2050. (2013). *Deliverable 1.2: Structuring of uncertainties, options and boundary conditions for the implementation of EHS.* Retrieved October 2, 2018, from http://www.e-highway2050.eu/fileadmin/documents/Results/eHighway2050_D1_2.pdf

e-Highway2050. (2013). *e-Highway2050*. Retrieved from http://www.e-highway2050.eu/e-highway2050/

EirGrid. (2017). *Tomorrow's Energy Scenarios 2017: Planning our Energy Future.* Dublin: EirGrid Plc. Retrieved August 2018, from http://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid-Tomorrows-Energy-Scenarios-Report-2017.pdf

ENTSO-E. (2018). *TYNDP 2018*. Retrieved April 2018, from https://tyndp.entsoe.eu/tyndp2018/

ENTSO-E. (2018). *TYNDP 2018 Scenario Report: Main Report.* Retrieved February 2018, from https://docstore.entsoe.eu/Documents/TYNDP%20documents/TYNDP2018/Scenario_Report_2018_Final.pdf

European Commission. (2012). *Energy Roadmap 2050.* Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/2012_energy_roadmap_2050_en_0.pdf

European Commission. (2016). Retrieved from https://ec.europa.eu/energy/en/data-analysis/energy-modelling

European Commission. (2016). *Energy Modelling*. Retrieved from https://ec.europa.eu/energy/en/data-analysis/energy-modelling

European Commission. (2016). *EU Reference Scenario 2016: Energy Transport and GHG emissions - Trends to 2050.* Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf

European Commission. (2016). Network Code on Requirements for Generators. *COMMISSION REGULATION (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators*.

European Commission. (2016). *REPORT FROM THE COMMISSION: Final Report of the Sector Inquiry on Capacity Mechanisms.* Brussels. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/swd_2016_385_f1_other_staff_working_paper_en_v3_p1_870001.pdf

European Commission. (2018). *EMHIRES dataset Part 1: Wind power generation*. Retrieved from Strategic Energy Technologies Information System : https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/emhires-dataset-part-i-wind-power-generation

EU-SysFlex. (2018). *Deliverable 2.1 State-of-the-Art Literature Review of System Scarcities at High Levels of Renewable Generation.*

EU-SysFlex. (2018). *Deliverable 2.3 Models for Simulating Technical Scarcities on the European Power System with High Levels of Renewable Generation.*

Gonzalez Aparicio, I., Zucker, A., Careri, F., Monforti-Ferrario, F., Huld, T., & Badger, J. (2016). *EMHIRES dataset. Part 1: Wind Power Generation. European Meteorological derived HIgh resolution RES generation time series for present and future scenarios.* JRC Science for Policy Report. doi:10.2790/831549

International Energy Agency; Nordic Council of Ministers. (2016). *Nordic Energy Technology Perspectives 2016: Cities, flexibility and pathways to carbon-neutrality.* doi:10.1787/9789264257665-en

Kiviluoma, J., Rinne, E., Helisto, N., & Azevado, M. (2014). *Modelling framework for power systems.* JULKAISIJA – UTGIVARE. Retrieved from https://www.vtt.fi/inf/pdf/technology/2014/T196.pdf

Lehtilä, A., Honkatukia, J., & Koljonen, T. (2014). *Lehtilä A, Honkatukia J, Koljonen T. Ydinvoimapäätösten energia- ja kansantaloudelliset vaikutukset.* Espoo, Finland: Ministry of Economic Affairs and Employment. doi:VTT report VTT-R-0370414

RTE. (2017). *Bilan previsionnel de l'equilibre offre-demande d'electricite en France.* Retrieved from https://www.rte-france.com/sites/default/files/bp2017_complet_vf.pdf

Statistics Sweden. (2017). Electricity supply, district heating and supply of natural gas 2016. Retrieved from http://www.scb.se

ANNEX I. SUMMARY OF DEMAND TABLES

Annex providing tables of data for the demand portfolio assumptions and outputs for each of the EU-SysFlex Core Scenarios

TABLE 18: ELECTRICITY DEMAND BY COUNTRY

	Energy Transition	Renewable Ambition
Country	**Final energy demand (TWh_e)**	**Final energy demand (TWh_e)**
AT	73	83
BE	89	108
CZ	66	79
DE	559	580
DK	36	44
EE	8	10
ES	257	291
FI	84	96
FR	469	548
HU	39	47
IE	28	34
IT	314	395
LT	10	12
LU	8	12
LV	8	10
NL	116	133
PL	168	202
PT	48	51
SE	144	166
SK	31	34
UK	356	438

ANNEX II. SUMMARY OF GENERATION TABLES

TABLE 19: TOTAL ANNUAL ELECTRICITY PRODUCTION BY FUEL TYPE AND BY COUNTRY IN THE CONTINENTAL MODEL IN ENERGY TRANSITION SCENARIO

	Energy Transition											
Country	Coal (GWh$_e$)	Nuclear (GWh$_e$)	Oil (GWh$_e$)	Gas (GWh$_e$)	Other fuels (GWh$_e$)	Biomass (GWh$_e$)	Wind (GWh$_e$)	Solar (GWh$_e$)	Geothermal and other Res (GWh$_e$)	Hydro (GWh$_e$)	Production (TWh$_e$)	Net Import (KTOE)
AT	3 290	0	67	14 589	0	4 060	10 050	3 312	11	44 553	80	280
BE	42	0	709	42 794	0	4 917	19 266	4 013	0	571	72	2 211
CH	0	8 082	0	4 014	0	3 288	2 122	0	0	39 829	57	2 041
CZ	38 739	27 594	0	10 047	0	3 669	878	2 276	2	2 561	86	-652
DE	231 939	0	3 056	108 810	0	53 400	128 324	60 513	969	23 820	611	1 361
DK	3 144	0	41	3 346	0	8 295	19 645	768	0	24	35	344
EE	6 898	0	0	577	0	920	1 011	1	0	33	57	78
ES	15 179	57 521	1 611	49 876	0	8 960	72 043	48 361	0	33 500	287	402
FI	9 821	28 850	280	11 572	0	20 564	7 194	14	0	15 124	93	-123
FR	69	385 062	341	12 047	0	20 256	83 418	41 048	2 011	64 139	608	-5 512
HU	2 113	34 387	0	2 219	0	1 921	890	97	65	232	42	412
IE	3 883	0	6	14 764	0	1 165	11 491	16	0	906	32	-82
IT	44 668	0	7 760	122 447	0	25 556	32 732	34 027	6 210	49 749	323	2 644
LT	0	9 377	0	2 739	0	972	828	64	0	440	40	-115
LU	0	0	24	3 503	0	239	512	122	0	146	5	410
LV	88	0	0	2 826	0	811	653	2	0	3 160	29	170
NL	20 754	4 047	57	61 569	0	17 607	27 598	5 004	0	105	137	-567
NO	0	0	0	5 438	0	864	15 819	0	0	138 000	160	-466
PL	132 075	0	471	30 214	0	15 892	21 665	84	0	2 765	203	117
PT	0	0	1 289	5 139	0	2 919	15 588	4 229	208	18 871	48	442
SE	715	49 738	0	11 143	0	20 890	22 375	75	0	69 800	175	-1 036
SK	1 877	29 384	92	346	0	908	26	619	0	5 045	38	-223
UK	3 676	107 051	2 893	108 350	0	65 945	95 394	8 985	258	5 469	398	1 063

TABLE 20: TOTAL ANNUAL ELECTRICITY PRODUCTION BY FUEL TYPE AND BY COUNTRY IN THE CONTINENTAL MODEL IN RENEWABLE AMBITION SCENARIO

	Renewable Ambition											
Country	**Coal (GWh$_e$)**	**Nuclear (GWh$_e$)**	**Oil (GWh$_e$)**	**Gas (GWh$_e$)**	**Other fuels (GWh$_e$)**	**Biomass (GWh$_e$)**	**Wind (GWh$_e$)**	**Solar (GWh$_e$)**	**Geothermal and other Res (GWh$_e$)**	**Hydro (GWh$_e$)**	**Production (TWh$_e$)**	**Net Import (KTOE)**
AT	30	0	0	17 464	0	6 824	15 410	5 060	11	45 776	91	206
BE	0	0	0	57 668	0	7 233	27 498	5 146	49	624	98	1 794
CH	0	0	0	0	0	10 486	3 552	9 780	0	50 153	74	188
CZ	17 948	54 467	0	11 840	0	7 608	1 782	2 967	2	3 877	100	-658
DE	136 854	0	552	124 671	0	74 801	195 659	83 044	969	30 665	647	1 287
DK	127	0	114	8 406	0	9 768	24 847	803	0	24	44	461
EE	1 580	0	0	1 918	0	2 620	4 413	1	0	82	11	61
ES	540	0	1 484	44 263	0	12 517	127 648	107 167	0	34 829	328	-376
FI	1 475	41 565	12	7 865	0	24 864	8 407	20	0	16 398	101	457
FR	0	246 066	20	39 283	0	28 905	171 302	77 182	6 920	77 815	647	-2 473
HU	0	28 346	0	11 376	0	3 558	3 562	626	65	1 072	49	462
IE	0	0	7	14 723	0	2 339	17 516	16	0	1 499	36	89
IT	0	0	864	143 734	0	63 655	62 047	87 928	5 749	53 875	418	1 677
LT	0	9 377	0	3 200	0	1 474	2 338	66	0	1 079	18	-290
LU	0	0	1	7 227	0	328	990	154	0	160	9	420
LV	76	0	0	2 810	0	1 541	1 861	2	0	3 330	10	113
NL	2 097	0	109	87 522	0	21 693	39 353	5 416	0	105	156	-634
NO	0	0	0	1 992	0	0	17 981	727	0	141 240	162	-1 026
PL	63 563	69 258	292	41 710	0	20 850	44 968	303	0	4 403	245	127
PT	0	0	476	1 379	0	3 985	19 219	7 682	208	19 136	52	339
SE	9	65 100	0	11 744	0	27 121	29 983	85	0	75 687	210	-1 768
SK	3 170	24 479	0	3 676	0	3 097	373	1 268	0	5 751	42	-205
UK	3 537	144 929	534	147 690	0	55 324	130 616	9 457	280	5 557	498	471

II.1 PAN EUROPEAN POWER SYSTEM GENERATION PORTFOLIO (INSTALLED CAPACITIES)

TABLE 21 : INSTALLED CAPACITIY (MW) BY FUEL TYPE AND BY COUNTRY IN THE ENERGY TRANSITION SCENARIO

Country	Energy Transition															
	Net Generation Capacity	Nuclear energy	Renewable energy	Hydro (pumping excluded)	Wind	Solar	Other renewables (tidal etc.)	Thermal power	of which cogeneration units	of which CCS	Solids fired	Gas fired	Oil fired	Biomass-waste fired	Hydrogen plants	Geothermal heat
AT	26 040	0	21 121	13 756	4 545	2 821	0	4 919	2 668	0	778	2 902	423	813	0	2
BE	22 284	0	10 902	177	6 907	3 818	0	11 382	1 264	0	16	10 331	215	820	0	0
CH	22 146	1 166	19 020	17 719	1 301	0	0	1 960	0	0	0	1 364	8	588	0	0
CZ	18 911	4 006	3 987	1 109	488	2 391	0	10 918	2 941	0	8 797	1 783	64	274	0	0
DE	209 097	0	137 031	5 857	67 214	63 959	0	72 066	12 493	0	36 775	26 978	1 248	6 894	1	170
DK	12 857	0	7 300	10	6 452	838	0	5 558	4 597	0	1 472	999	217	2 870	0	0
EE	2 288	0	454	8	445	1	0	1 833	355	0	1 408	272	0	154	0	0
ES	115 578	7 399	71 246	16 795	29 888	24 564	0	36 933	2 791	0	3 968	28 091	2 952	1 923	0	0
FI	18 807	3 398	6 395	3 461	2 915	19	0	9 014	5 584	0	1 844	3 233	607	3 330	0	0
FR	157 433	59 493	80 704	23 635	30 771	25 382	916	17 236	4 014	0	3 780	8 344	1 679	3 431	0	3
HU	8 463	4 482	640	57	477	106	0	3 342	1 574	0	396	2 531	5	357	0	52
IE	8 836	0	4 448	295	4 135	19	0	4 388	312	0	842	3 165	173	208	0	0
IT	114 442	0	59 078	18 939	15 577	24 562	0	55 364	14 401	0	5 098	41 739	2 332	5 409	12	773
LT	3 263	1 117	657	116	467	74	0	1 489	965	0	0	1 350	0	139	0	0
LU	1 199	0	478	45	302	131	0	721	306	0	0	682	4	35	0	0
LV	3 113	0	1 877	1 589	286	2	0	1 236	1 096	0	21	1 091	15	108	0	0
NL	35 295	485	15 719	37	10 096	5 586	0	19 092	5 014	250	4 429	12 289	66	2 308	0	0
NO	44 162	0	42 157	35 817	5 540	800		2 005	0	0	4	1 864	2	135	0	0
PL	39 845	0	11 478	1 039	10 339	99	0	28 367	7 816	0	20 704	5 403	155	2 105	0	0
PT	24 198	0	18 446	9 971	6 302	2 172	0	5 752	1 546	0	0	4 368	691	664	0	29
SE	39 871	6 949	25 842	16 742	9 013	88	0	7 079	5 927	0	128	3 280	510	3 161	0	0
SK	8 440	4 020	2 424	1 725	19	680	0	1 996	778	0	483	1 097	84	332	0	0
UK	114 323	13 107	46 377	1 791	33 421	11 043	122	54 839	14 861	833	501	35 928	1 167	17 244	0	0

TABLE 22: INSTALLED CAPACITIY (MW) BY FUEL TYPE AND BY COUNTRY IN THE RENEWABLE AMBITION SCENARIO

	Renewable Ambition															
Country	Net Generation Capacity	Nuclear energy	Renewable energy	Hydro (pumping excluded)	Wind	Solar	Other renewables (tidal etc.)	Thermal power	of which cogeneration units	of which CCS units	Solids fired	Gas fired	Oil fired	Biomass-waste fired	Hydrogen plants	Geothermal heat
AT	28 589	0	24 854	14 042	6 803	4 009	0	3 735	3 431	0	36	2 850	0	846	0	2
BE	30 082	0	14 265	193	9 331	4 722	19	15 816	2 934	0	0	14 810	2	1 003	0	0
CH	34 543	0	33 243	22 312	1 000	9 931	0	1 300	0	0	0	0	0	1 300	0	0
CZ	19 084	6 848	5 320	1 393	838	3 089	0	6 916	3 913	1 320	3 098	3 153	24	641	0	0
DE	252 774	0	179 860	7 170	86 549	86 141	0	72 914	15 542	7 920	24 057	41 426	674	6 586	1	170
DK	15 085	0	8 090	10	7 237	844	0	6 994	4 732	400	34	4 298	58	2 604	0	0
EE	3 528	0	1 734	20	1 713	1	0	1 794	351	0	468	959	0	367	0	0
ES	131 172	0	113 658	17 158	47 142	49 359	0	17 514	3 279	0	97	14 482	782	2 153	0	0
FI	19 447	4 951	6 921	3 755	3 140	25	0	7 575	5 340	0	327	4 065	49	3 134	0	0
FR	206 513	32 276	132 157	26 559	57 569	45 200	2 829	42 080	5 294	400	2 892	34 924	625	3 636	0	3
HU	10 093	3 692	2 475	267	1 616	592	0	3 926	1 422	0	3	3 483	0	388	0	52
IE	11 156	0	6 214	442	5 753	19	0	4 941	377	0	0	4 627	1	313	0	0
IT	156 207	0	102 310	19 588	25 957	56 765	0	53 897	13 377	0	1 901	45 062	128	6 114	0	692
LT	3 282	1 117	1 503	286	1 144	74	0	661	655	0	0	495	0	166	0	0
LU	1 978	0	693	49	485	160	0	1 285	186	0	0	1 244	3	37	0	0
LV	3 308	0	2 350	1 665	683	2	0	958	915	0	21	803	0	134	0	0
NL	42 701	0	18 714	37	12 806	5 871	0	23 987	5 617	250	3 496	17 788	58	2 644	0	0
NO	43 178	0	42 667	36 932	4 535	1 200	0	511	0	0	0	435	0	76	0	0
PL	51 109	8 250	20 654	1 427	18 877	350	0	22 205	9 530	4 950	9 983	9 143	63	3 016	0	0
PT	22 092	0	20 741	9 971	7 103	3 666	0	1 351	1 192	0	0	631	123	569	0	29
SE	46 402	9 023	29 224	17 909	11 220	96	0	8 155	7 976	0	8	4 734	0	3 412	0	0
SK	8 063	3 020	3 170	1 888	164	1 119	0	1 873	961	330	449	958	3	462	0	0
UK	136 895	17 302	54 673	1 818	41 468	11 255	130	64 920	8 408	833	448	46 102	339	18 032	0	0

II.2 NORDIC POWER SYSTEM GENERATION PORTFOLIO (INSTALLED CAPACITIES)

TABLE 23: INSTALLED CAPACITIES FOR THE NORDIC POWER SYSTEM SIMULATION IN THE ENERGY TRANSITION SCENARIO

Installed Capacity by Fuel Type (MW_e)	Energy Transition			
	Sweden	**Finland**	**Denmark**	**Norway**
Solids	128	1 844	1 472	-
Nuclear	6 949	3 398	-	-
Gas, Distillate Oil or Heavy Fuel Oil	3 790	3 840	1 216	1 863
Conventional Fuel Generation	10 867	9 082	2 688	1 863
Wind (Onshore)	N/A	N/A	N/A	N/A
Wind (Offshore)	N/A	N/A	N/A	N/A
Wind-Total	10 299	2 737	8 306	5 540
Hydro	16 742	3461	10	35 800
Biomass/LFG (including Biomass CHP)	3 161	1 830	2 870	135
Solar PV	86	16	877	800
Ocean (Wave/Tidal)	-	-	-	-
Renewable Generation	30 287	8 044	12 063	42 275
Pumped Storage	-	-	-	-
Small Scale Battery Storage	-	-	-	-
Large Scale Battery Storage	-	-	-	-
DSM	1 050	530	490	730
Conventional CHP or waste	5 929	5 570	4 596	175
Total Capacity	41 155	18 627	14 750	44 138

TABLE 24: INSTALLED CAPACITIES FOR NORDIC POWER SYSTEM SIMULATION IN THE RENEWABLE AMBITION SCENARIO

Installed Capacity by Fuel Type (MW_e)	**Renewable Ambition**			
	Sweden	**Finland**	**Denmark**	**Norway**
Solids	8	327	34	-
Nuclear	9 023	4 951	-	-
Gas, Distillate Oil or Heavy Fuel Oil	4 734	4 113	4 356	1 863
Conventional Fuel Generation	13 765	9 392	4 390	1 863
Wind (Onshore)	N/A	N/A	N/A	N/A
Wind (Offshore)	N/A	N/A	N/A	N/A
Wind-Total	13 801	3 199	10 505	6 745
Hydro	17 909	3 755	10	35 800
Biomass/LFG (including Biomass CHP)	3 412	1 634	2 604	135
Solar PV	97	23	916	800
Ocean (Wave/Tidal)	-	-	-	-
Renewable Generation	35 220	8 612	14 036	43 480
Pumped Storage	-	-	-	-
Small Scale Battery Storage	-	-	-	-
Large Scale Battery Storage	-	-	-	-
DSM	1 050	530	490	730
Conventional CHP or waste	6 047	4 975	3 660	171
Total Capacity	48 985	19 504	18 426	45 343

TABLE 25: INSTALLED CAPACITIES FOR NORDIC POWER SYSTEM SIMULATION IN THE HIGH SOLAR SCENARIO

Installed Capacity by Fuel Type (MW$_e$)	**High Solar**			
	Sweden	Finland	Denmark	Norway
Solids	128	700	34	-
Nuclear	6 949	3 398	-	-
Gas, Distillate Oil or Heavy Fuel Oil	3 790	4 807	1 216	1 863
Conventional Fuel Generation	10 867	8 905	1 250	1 863
Wind (Onshore)	N/A	N/A	N/A	N/A
Wind (Offshore)	N/A	N/A	N/A	N/A
Wind-Total	13 801	4140	10 505	6 745
Hydro	16 742	3 461	10	35 800
Biomass/LFG (including Biomass CHP)	2 800	1 300	2 870	135
Solar PV	5 384	2 853	5 113	2 972
Ocean (Wave/Tidal)	-	-	-	-
Renewable Generation	38 727	11 754	18 499	45 652
Pumped Storage	-	-	-	-
Small Scale Battery Storage	-	-	-	-
Large Scale Battery Storage	-	-	-	-
DSM	1 050	530	490	730
Conventional CHP or waste	5 568	5 534	3 530	175
Total Capacity	49 595	22 159	19 749	47 515

II.3 POLAND POWER SYSTEM GENERATION PORTFOLIO (INSTALLED CAPACITIES)

TABLE 26: COMPARISON BETWEEN INSTALLED CAPACITIES IN POLAND IN DIFFERENT SCENARIOS

Installed Capacity by Fuel Type (MW$_e$)	**EU-SysFlex Core Scenarios**		**Continental Europe Network Sensitivities**	
	Energy Transition	**Renewable Ambition**	**Going Green**	**Distributed Renewables**
Coal	20 704	9 983	20 704	20 704
Gas	5 403	9 143	5 403	5 403
Distillate Oil or Heavy Fuel Oil	155	63	473	473
Conventional Fuel Generation	**26 262**	**19 189**	**25 980**	**25 980**
Wind (Onshore)	9 139	16 877	16 360	16 360
Wind (Offshore)	1 200	2 000	3 500	3 500
Wind-Total	10 339	18 877	19 860	19 860
Hydro	1 039	1 427	1 039	1 039
Solar PV	99	350	3 260	3 260
Biomass	2 105	3 016	2 105	2 105
Renewable Generation	**13 582**	**23 670**	**26 264**	**26 264**
Conventional CHP or waste	**7 816**	**9 530**	7 816	7 816
Nuclear	-	8 250	-	-
Total Capacity	**39 844**	**51 109**	**52 527**	**52 527**

II.4 IRELAND AND NORTHERN IRELAND POWER SYSTEM GENERATION PORTFOLIO (INSTALLED CAPACITIES)

TABLE 27: IRELAND AND NORTHERN IRELAND PORTFOLIOS FOR THE SCENARIOS AND FOR THE NETWORK SENSITIVITIES

Installed Capacity by Fuel Type (MW$_e$)	EU-SysFlex Scenarios		IE and NI Network Sensitivities		
	Energy Transition	Renewable Ambition	Steady Evolution	Low Carbon Living	Consumer Action
Solids	855	-	-	-	-
Gas	4 234	5 657	5 657	5 207	5 657
Distillate Oil or Heavy Fuel Oil	473	169	389	273	273
Conventional Fuel Generation	**5 562**	**5 826**	**6 096**	**5 530**	**5 980**
Wind (Onshore)	5 650	7 268	6 678	7 040	6 922
Wind (Offshore)	25	25	700	3 000	1 000
Wind-Total	5 675	7 293	7 378	10 040	7 922
Hydro	237	237	237	237	237
Biomass/LFG (including Biomass CHP)	287	715	487	847	528
Solar PV	369	420	900	3 916	2 916
Ocean (Wave/Tidal)	-	-	50	98	73
Renewable Generation	**6 568**	**8 260**	**9 052**	**15 188**	**11 725**
Pumped Storage	292	292	292	652	292
Small Scale Battery Storage	-	-	200	500	800
Large Scale Battery Storage	-	-	350	1 300	500
DSM	-	-	500	750	1 000
DC Interconnection	1 650	2 150	1 650	2 150	1 650
Conventional CHP or waste	327	503	290	309	318

ANNEX III. COMMODITY PRICES

III.1 COMMODITY PRICES FOR THE SCENARIO ENERGY TRANSITION

TABLE 28: COMMODITY PRICES (FUEL PRICES PROVIDED BY DG ENERGY TO ENTSO-E FOR EUCO30 SCENARIO) (ENTSO-E, 2018)

	Prices (€/net GJ)
Nuclear	0.47
Lignite	2.3
Hard coal	4.3
Gas	6.9
Light oil	20.5
	Price (€/ton)
CO_2	27

III.2 COMMODITY PRICES FOR THE SCENARIO RENEWABLE AMBITION

TABLE 29: COMMODITY PRICES (EU REFERENCE SCENARIO 2016 - 2050) (EUROPEAN COMMISSION, 2016)

	Prices (€/net GJ)
Nuclear	0.47
Lignite	1.1
Hard coal	3.28
Gas	1.43
Light oil	17.06
	Price (€/ton)
CO_2	90