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Building blocks for a common vision for a decarbonised electricity system in the Penta region

Final report

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TABLE OF CONTENTS

1 EXECUTIVE SUMMARY 5

2 CONTEXT AND OBJECTIVES 7

3 METHODOLOGY 9

4 OBSERVATIONS DERIVED FROM THE SCENARIO AND LITERATURE REVIEW 12

4.1 EVOLUTION OF POWER DEMAND 12
4.1.1 POWER DEMAND IS EXPECTED TO INCREASE BY 35% TO 100% BY 2050 12
4.1.2 ROAD PASSENGER TRANSPORT AND LOW/MEDIUM-TEMPERATURE HEAT SUPPLY PERFECTLY SUITED FOR DIRECT ELECTRIFICATION 16
4.1.3 HYDROGEN DEMAND DRIVES NEEDS FOR SUBSTANTIAL ELECTROLYSER INVESTMENTS, WITH HYDROGEN IMPORTS REDUCING ADDITIONAL PRESSURE ON POWER SYSTEMS 19
4.1.4 THERMAL RENOVATION IS A PRECONDITION TO BUILDING STOCK DECARBONISATION, WHICH CANNOT RELY ON HEAT PUMPS ROLL-OUT ONLY 22
4.1.5 DEMAND-SIDE FLEXIBILITY IS KEY TO FACILITATE SYSTEM-FRIENDLY ELECTRIFICATION 23
4.2 THE FUTURE OF ELECTRICITY SUPPLY 26
4.2.1 PENTA POWER PRODUCTION IS PREDOMINANTLY OR FULLY DECARBONISED BY 2035 26
4.2.2 MASSIVE VRES DEPLOYMENT IN ALL SCENARIOS 27
4.2.3 THE NEED FOR FLEXIBILITY WILL INCREASE SIGNIFICANTLY 30
4.2.4 REGIONAL COOPERATION AS KEY LEVER FOR A LEAST-COST ENERGY SYSTEM TRANSFORMATION 32
4.3 POWER SYSTEM STABILITY: THE ROLE OF STORAGE AND GRIDS 36
4.3.1 ENERGY STORAGE DEVELOPMENT IS KEY TO ENSURE ADEQUACY IN THE PENTA REGION 36
4.3.2 DECENTRALISED ELECTRICITY PRODUCTION AND USE DRIVE NEED TO REINFORCE DISTRIBUTION GRIDS 39
4.3.3 ONLY REINFORCED TRANSMISSION CAN CONNECT NEW ELECTRICITY PRODUCTION AND CONVERSION SITES AND COPE WITH RISING TRANSIT POWER FLOWS 40
4.3.4 CROSS-BORDER EXCHANGE CAPACITIES AND FLOWS INCREASE TO FACILITATE REGIONAL COOPERATION. 42
4.3.5 INTEGRATED INFRASTRUCTURE PLANNING AS PREREQUISITE OF A COST-EFFICIENT AND TIMELY TRANSITION 43
4.4 METHODOLOGIES UNDERLYING THE SCENARIO ASSESSMENTS 45

5 CONVICTIONS AND LINK TO THE UNDERLYING OBSERVATIONS 48

5.1 POWER SECTOR DECARBONISATION BY 2035 48
5.2 RENEWABLES ARE THE MAIN PILLAR OF DECARBONISATION 49
5.3 “ENERGY EFFICIENCY FIRST” RELEASES PRESSURE FROM THE POWER SYSTEM 50

5.4 DIRECT ELECTRIFICATION COMES WITH IMMEDIATE BENEFITS 51
5.5 DECARBONISED MOLECULES WILL PLAY A LIMITED BUT CRUCIAL ROLE 51
5.6 HYDROGEN ECONOMY NEEDS TO BE ESTABLISHED NOW 52
5.7 POWER GRID CAPACITIES NEED TO INCREASE SUBSTANTIALLY 53
5.8 A COORDINATED APPROACH TO ENERGY SYSTEM PLANNING 54
5.9 FLEXIBILITY - A KEY ELEMENT OF THE ENERGY TRANSITION 54
5.10 ADDITIONAL POWER DEMAND CAN AND MUST BE FLEXIBLE 55
5.11 ENERGY STORAGE FACILITATES RES INTEGRATION 56
5.12 THE TRANSITION REQUIRES A FUTURE-PROOF MARKET DESIGN 56

6 CONCLUSIONS AND RECOMMENDATIONS 57

7 ANNEX – ACTIONS 60

7.1 MAPPING OF OBSERVATIONS, CONVICTIONS AND ACTIONS 60
7.2 ACTIONS 62
7.2.1 CO2.1 - ACHIEVE A DECARBONISED PENTA POWER SECTOR BY 2035 62
7.2.2 RES.1 – PENTA OBJECTIVES FOR RES SHARE IN POWER GENERATION 63
7.2.3 RES.2 - JOINT TRAINING STRATEGY FOR MORE SKILLED LABOUR IN THE FIELD OF RES INSTALLATIONS 65
7.2.4 RES.3 - JOINT RES PROJECTS AND FRAMEWORKS 66
7.2.5 RES.4 - “RES MADE IN PENTA” INITIATIVE 68
7.2.6 EE.1 - PENTA BUILDING DECARBONISATION INITIATIVE 69
7.2.7 ELEC.1 - TRANS-PENTA EV CHARGING NETWORK 70
7.2.8 ELEC.2 - JOINT OBJECTIVE FOR HEAT PUMP ROLL-OUT 72
7.2.9 HYDROGEN.1 - JOINT PENTA ELECTROLYSER OBJECTIVE AND HYDROGEN STRATEGY 73
7.2.10 HYDROGEN.2 - JOINT HYDROGEN IMPORT STRATEGY 76
7.2.11 GRIDS.1 - INCREASE THE PENTA CROSS-BORDER INTERCONNECTION LEVEL 78
7.2.12 GRIDS.2 - REGULAR BEST PRACTICE SHARING ON DISTRIBUTION GRIDS 81
7.2.13 PLANNING.1 - JOINT NECP SCENARIO PREPARATION 83
7.2.14 PLANNING.2 - PENTA NETWORK PLANNING INITIATIVE / JOINT PENTA NETWORK DEVELOPMENT PLAN 84
7.2.15 PLANNING.3 - PROMOTE BEST PRACTICE RECOMMENDATIONS FOR FUTURE SYSTEM MODELLING 86
7.2.16 DSF.1 - PENTA SMART DEMAND INITIATIVE 88
7.2.17 STORAGE.1 - JOINT PENTA STORAGE DEPLOYMENT INITIATIVE 91

8 REFERENCES 94

1 Executive summary

The Pentalateral Energy Forum (short Penta) is a framework for regional cooperation between Austria, Belgium, France, Germany, Luxembourg, Switzerland and the Netherlands. The participating countries have been working since 2005 on a voluntary basis towards more closely integrating their domestic electricity markets and are thereby taking the lead in Europe. In 2021 Penta countries ministers agreed that **a joint 2050 vision for a decarbonised electricity system will keep Penta at the forefront of the energy transition.**

The present study shall help to create a common vision for a decarbonised electricity system at the latest by 2050, as part of the Pentalateral Energy Forum's endeavour for regional integration towards a European and reliable electricity market. The present study builds on previous work and broadens and deepens the analysis to work towards a common understanding and vision on a decarbonized electricity system by 2050, with intermediate steps in 2030 and 2040.

The preparation of the study relied on a 4-step approach, which is illustrated in Figure 1.

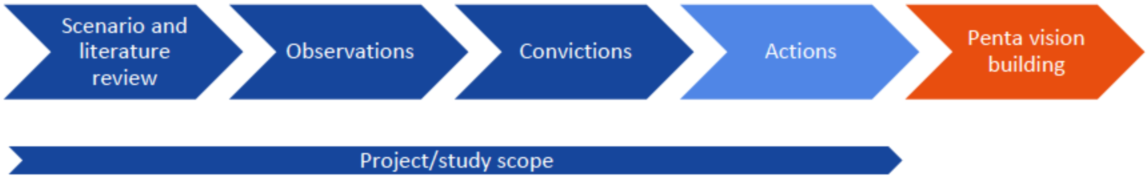

Figure 1 - Four-step approach underlying the preparation of this study

A review of existing scenario assessments and technical reports identified likely developments and remaining uncertainties in the different energy system transformation pathways published by national and international stakeholders. The analysis of the scenarios and technical reports was organised along four major dimensions: power demand, supply, power system stability and methodologies underlying the scenario assessments. For each dimension, a set of major **observations** was identified, which indicate likely developments and remaining uncertainties in the transformation pathways analysed. Subsequently, the observations were condensed and translated into twelve **convictions**, which may be understood as *necessary conditions* to facilitate the decarbonisation of the power sector and ultimately of the entire economy by 2050 at the latest. Finally, a non-exhaustive list of exemplary, indicative **actions** illustrates how the convictions could be put into effect. **The twelve convictions are as follows**:

1. **Power sector decarbonisation** needs to be decarbonized as early as possible, ideally by 2035;
2. **Renewables** are the main pillar of power sector decarbonisation, with solar power and wind representing the biggest share – but requiring an accelerated deployment;
3. "**Energy efficiency first**" reduces the expected increase in power demand and releases pressure from the power system;

4. **Direct electrification** is a no-regret option in various domains and comes with immediate benefits;
5. **Decarbonised molecules** will play a limited but crucial role in hard-to abate sectors;
6. The **hydrogen economy** needs to be established now, and Penta is particularly well placed to initiate and drive forward this process;
7. **Power grid capacities** need to increase substantially, through more efficient operation and grid reinforcement, at all grid levels: distribution, transmission and cross-border;
8. A **coordinated approach to energy system planning** is key to achieve a timely and cost-efficient system transformation avoiding stranded assets;
9. **Flexibility** is a key element of the energy transition and flexibility needs for power system stability will significantly increase in the future on all time scales;
10. Additional **power demand can and must be flexible** (i.e., operated in an electricity price sensitive way) in particular for electric vehicles, heat pumps and electrolysers;
11. **Energy storage** facilitates RES integration, yet storage potentials (e.g., for hydro and hydrogen) are not equally distributed and require regional cooperation for a coordinated exploitation;
12. The transition **requires a future-proof market design**, to trigger the investments into the beforementioned technologies and to efficiently ensure resource and transmission adequacy.

These building blocks may be used by the Pentalateral Energy Forum for the building of a joint 2050 vision.

2 Context and objectives

Context

The Pentalateral Energy Forum (short Penta) is a framework for regional cooperation between Austria, Belgium, France, Germany, Luxembourg, Switzerland and the Netherlands. The participating countries have been working since 2005 on a voluntary basis towards more closely integrating their domestic electricity markets and are thereby taking the lead in Europe.

In 2020, a first comparison of existing long-term scenarios on the electricity sector development up to 2050 by the Penta countries and the European Commission was conducted by a consultant, identifying similarities and differences in perspectives. However, the consultants also noted that the studies analysed partly differ quite significantly regarding basic assumptions and underlying methodologies, which might be one possible explanation for some of the differences observed. Furthermore, the underlying studies are of different age and were therefore developed based on different states of play with respect to political, technological and economic circumstances. Feedback by Penta members demonstrated the need for further work and discussions in Penta, especially in order to:

- **broaden the basis of studies** to be considered, as more updated long-term scenarios are expected to come (e.g. by ENTSO-E) reflecting more recent climate and energy targets, and some specific aspects might be better covered by dedicated studies and not so much by the long-term scenarios itself;
- **dive deeper into specific topics** so as to gain a more detailed understanding of future developments which could bridge the gap between the rather general statements (see ‘earlier research’) and the need for concrete action and intermediate steps towards 2050;
- create the **basis for a common understanding** of the expectations and challenges for building a future decarbonized electricity system in the Penta region.

Objectives

Ministers of the Pentalateral Energy Forum’s countries agreed in February 2021 that coming to a joint 2050 vision will keep Penta at the forefront. The present study shall help to create a common vision for a decarbonised electricity system (facilitating energy system decarbonisation by 2050 at the latest), as part of the Pentalateral Energy Forum’s endeavour for regional integration towards a European and reliable electricity market.

The present study builds on previous work and broadens and deepens the analysis to work towards a common understanding and vision on a decarbonized electricity and energy system by 2050, with intermediate steps in 2030 and 2040.

The study aims to analyse existing scenarios and technical analyses regarding the likely developments, identified certainties and remaining uncertainties regarding the energy system 2050 in the Penta region. The authors of this report establish building blocks facilitating the creation of a shared vision on a climate neutral electricity system in the Penta region, discussing the main elements and concrete steps, including intermediate steps for 2030 and 2040, with the focus on the specific topics.

3 Methodology

The preparation of the study relied on a 4-step approach, which is illustrated in Figure 2.

Figure 2 - Four-step approach underlying the preparation of this study

The identification of likely developments and remaining uncertainties in the different energy system transformation pathways published by national and international stakeholders relied on a **review of existing scenario assessments and technical reports**. The scenarios considered for the review were selected in close coordination with Penta, aiming for a representative, yet manageable number of scenarios. Scenarios were selected from the most recent publications, provided that they contain sufficiently detailed information to be included in the scenario comparison and subject to the condition of complete energy system decarbonisation by 2050 and a relevant level of regional cooperation. Nonetheless due to national ambitions evolving, the scenarios can differ from current national ambitions. Table 1 lists all national and international scenario-based assessments considered in this study. The full list of analysed reports is available in the bibliography, cf. Section 8.

Table 1 - Overview of national and international scenario assessments

Zone	Reference	Title	Scenarios
AT	(Austrian Federal Ministry for Sustainability and Tourism, 2019)	Integrated National Energy and Climate Plan for Austria	
BE, EU	(Elia Group, 2021)	Roadmap to net zero - Elia Group's vision on building a climate-neutral European energy system by 2050	All demand scenarios (ELEC and MOL pathways) and all supply scenarios (BAU x1.5, BAU x3, BAU x4)
BE	(DG Environment, 2021)	Scenarios for a climate neutral Belgium by 2050	Behaviour scenario
CH	(Bundesamt für Energie BFE, 2021)	Energieperspektiven 2050+	ZERO Basis and Zero B
CH	(Paul Scherrer Institute, 2021)	Long-term energy transformation pathways - Integrated scenario analysis with the Swiss times energy systems model	CLI Scenario
DE	(BMWi, 2021)	Langfristszenarien für die Transformation des Energiesystems in Deutschland 3	TN-Strom and TN-H2
DE	(Stiftung Klimaneutralität, Agora Energiewende, Agora Verkehrswende, 2021)	Towards a Climate-Neutral Germany by 2045	One single scenario

Zone	Reference	Title	Scenarios
DE	(Agora Energiewende, 2022)	Climate-neutral power system 2035. How the German power sector can become climate-neutral by 2035	One single scenario
FR	(ADEME, 2021)	Modélisation des trajectoires - Transition(s) 2050	S2 and S3 Nuc
FR	(RTE, 2022)	Futurs énergétiques 2050	M23 and N2
LU	(Luxembourg Ministry of the Environment, Climate and Sustainable Development, and Luxembourg Ministry of Energy and Spatial Planning, 2018)	Integrierter nationaler Energie- und Klimaplan Luxemburgs für den Zeitraum 2021-2030	Target Scenario
LU	(Creos, 2020)	Scenario Report 2040	Target Scenario
NL	(Netbeheer, 2021)	The Energy System of the Future	European Scenario and International Scenario
EU	(European Commission, 2018)	A Clean Planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy	1.5 TECH Scenario of the Long Term Strategy
EU	(ENTSO-E, ENTSOG, 2022)	TYNDP 2022	National Trends, Global Ambition and Distributed Energy

The analysis of the scenarios and technical reports was organised along 4 major dimensions:

1) **Demand**: Evolution of power demand, incl. demand from sector coupling, and demand side flexibility
2) **Supply**: Evolution of power generation mixes, role of selected technologies (RES, CCS, CCU)
3) **Power system stability**: the role of storage and grids
4) **Methodology**: modelling methodologies underlying the scenario assessments

For each dimension a set of major **observations** was identified, which indicate likely developments and remaining uncertainties in the transformation pathways analysed, cf. Section 4.

Subsequently, the observations were condensed and translated into twelve **convictions**, which may be understood as *necessary conditions* to facilitate the decarbonisation of the power sector and ultimately of the entire economy by 2050 at the latest, cf. Section 5.[1] These convictions represent the main outcome of the study and represent the building blocks that may be used for the building of a joint vision for a decarbonised electricity system of the Pentalateral Energy Forum.

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[1] A sub-set of draft convictions were discussed in November 2022 with an expert panel. We are grateful for the constructive feedbacks from: Nadine Berthomieu (ADEME), Jan Cihlar (Guidehouse), Samira Farahani (WaterstofNet), Tobias Fleiter (Fraunhofer ISI), Joao Gorenstein & Luc van Nuffel (Trinomics), Thomas Krutzler (Umweltbundesamt Österreich), Christian Redl (Agora Energiewende).

Finally, a non-exhaustive list of exemplary, indicative **actions** illustrates how the convictions could be put into effect. However, these actions should not be understood as proper recommendations as they would require a more in-depth impact assessment. They are available in the Annex, cf. Section 7.

4 Observations derived from the scenario and literature review

The identification of likely developments (entitled *observations* in the following) relied on an exhaustive review of existing scenario assessments and technical reports. The identified observations are clustered along the four major research dimensions: power demand (Section 4.1), electricity supply (Section 4.2), power system stability (Section 4.3) and the methodologies underlying to the scenario assessments (Section 4.4).

The focus is set on the power sector, with some observations addressing also connected domains of the energy system, notably hydrogen.

The identified remaining uncertainties in existing transition pathways are listed for each of the individual convictions derived from the observations (cf. Section 5).

4.1 Evolution of power demand

4.1.1 Power demand is expected to increase by 35% to 100% by 2050

Power demand in the Penta region is expected to increase by a minimum of 35% by 2050, and may more than double in some scenarios, driven by both direct and indirect electrification

Opposing trends are expected to impact the evolution of power demand. **Energy efficiency improvements and behavioural changes may delay or dampen the increase in power demand.** Figure 3 illustrates that the expected increase of 60% in power demand due to direct and indirect electrification of end-uses (disregarding the rise in power demand related to increased macro-economic drivers like population and economic activity) may be reduced by nearly two thirds to 24% thanks to energy efficiency efforts.

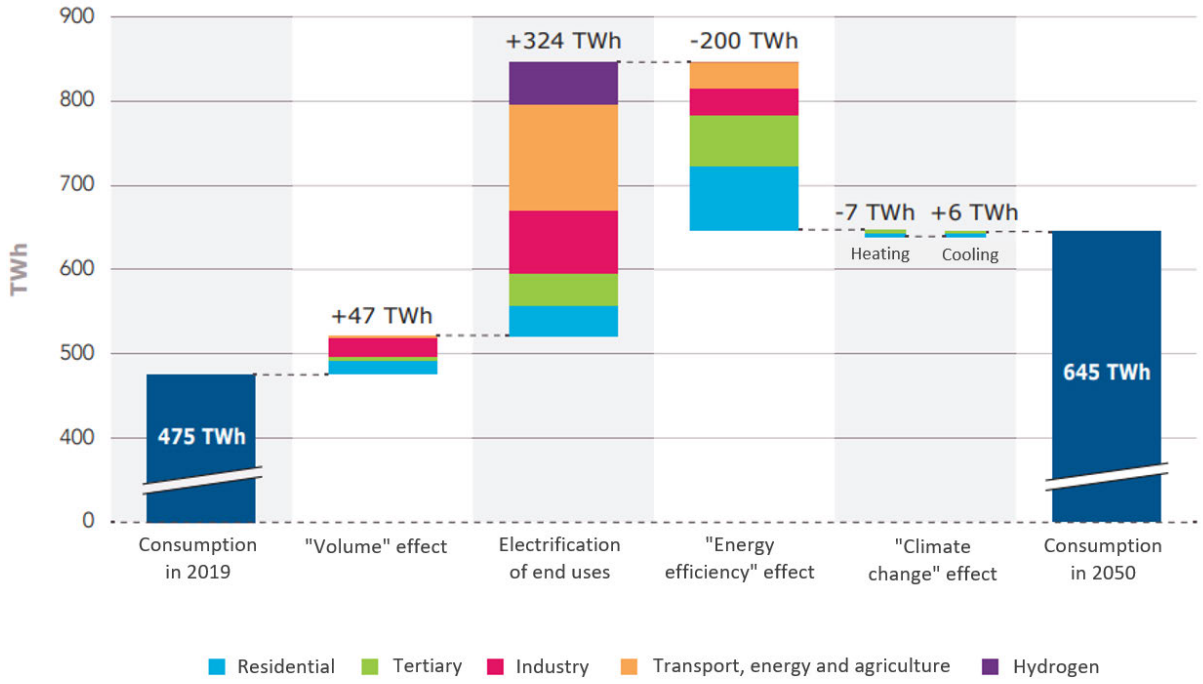

Figure 3 - Evolution of French power demand between 2019 and 2050. Source: (RTE, 2022).

Direct and indirect electrification are shifting the demand upwards. The impact of indirect electrification depends on the magnitude of deployment of electrolysis. As described in section 4.1.3, hydrogen imports are a lever to reduce domestic power demand for hydrogen production. The economic development and the relocation of the industry can strengthen one or the other direction.

The increase of the power demand (direct or indirect) varies significantly across countries and scenarios. Figure 4 illustrates the relative evolution of total power demand until 2050 compared to current levels for the different national and international scenarios. The orange-shaded area covers all scenarios with distinct information about the evolution of domestic power demand, whereas the scenarios MOL and ELEC from the Elia study (Elia Group, 2021) are not included in this range as they also include power demand required for the generation of e-fuels which may be met abroad (i.e., the generation of the e-fuels may take place outside Belgium, Germany or Europe, respectively).

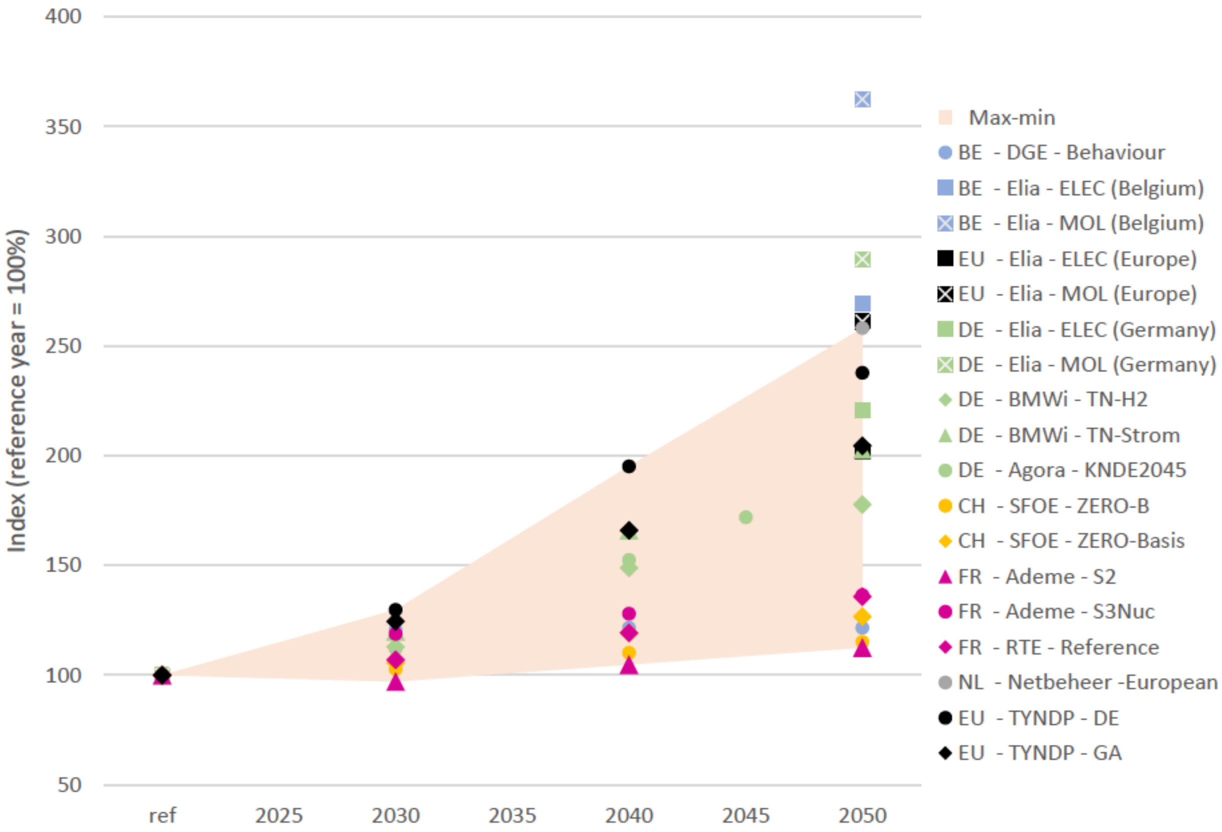

Figure 4 - Evolution of total power demand (% compared to ref year). Source: own illustration[2].

Figure 5 indicates the share of power demand required for hydrogen production in total power demand. This share reaches significant levels (above 5%) from 2040 onwards, and may make up for 35% of 2050 power demand. However, compared to the overall increase in power demand, the production of hydrogen (reflecting indirect electrification) does not represent the major driver of the increase in power demand, but direct electrification, cf. Figure 6. The major drivers for direct electrification are provided in the sub-sequent observation (Section 4.1.2).

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[2] The reference value for the Netherlands is based on Eurostat, it is the demand value for 2020.

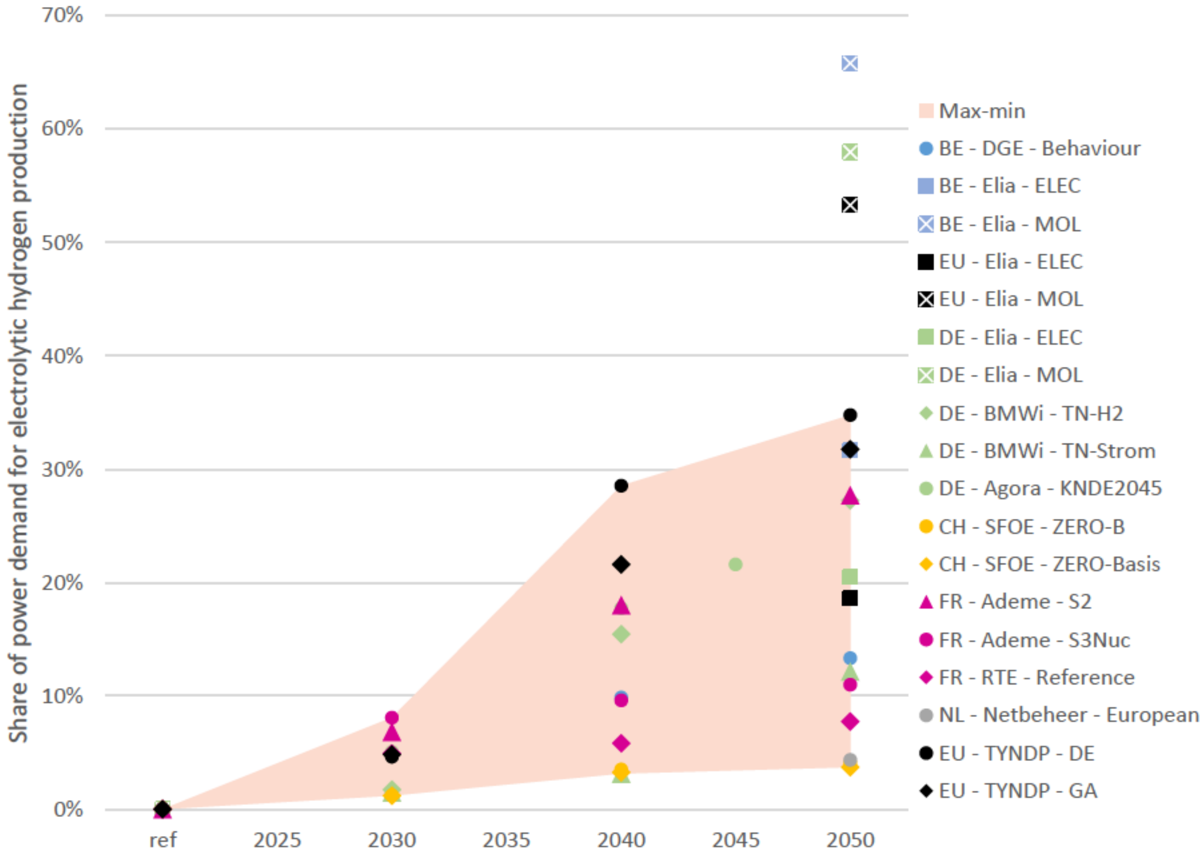

Figure 5 – Share of power demand for electrolytic hydrogen production in total power demand. Source: own illustration.

Countries currently relying strongly on gas, such as Germany and the Netherlands, are the ones with the higher rates of indirect electrification. This leads to higher growth of total power demand as indirect electrification is often less energy efficient than direct electrification (see Observation 4.1.2).

In the Netherlands, an increase in total power demand of at least 200% and up to 350% with domestic e-fuel synthesis is expected.

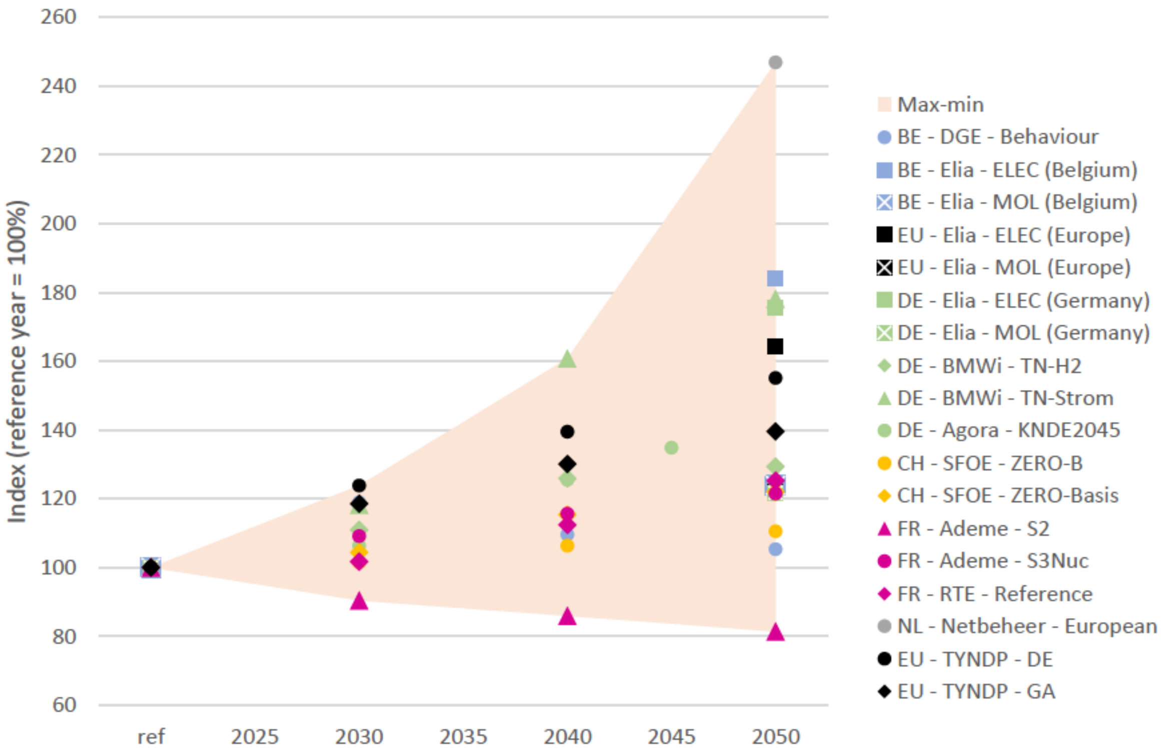

Figure 6 - Evolution of final (direct) power demand (%, compared to ref. year). Source: own illustration.

4.1.2 Road passenger transport and low/medium-temperature heat supply perfectly suited for direct electrification

There is a broad concordance across the studies reviewed, that several sectors and sub-sectors are particularly well suited for **direct electrification**, namely passenger road transport, buildings (ideally renovated, cf. Section 4.1.4), and low/medium-temperature heat supply in industry. Their shift from fossil energy carriers to the direct use of electricity comes with higher efficiency than indirect electrification[3]. **Indirect electrification** instead, that is the use of hydrogen and synthetic fuels (i.e.,

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[3] Indirect electrification relates to the use of hydrogen or hydrogen derivatives produced on the basis of electricity.

hydrogen derivatives), is commonly applied in particular in sectors where direct electrification is technically infeasible or comes with significant additional costs.[4]

For cost-efficient decarbonisation of **heat supply in buildings and industry,** a massive **heat pump roll-out** is considered in literally all scenarios. Small-scale heat pumps are more than five times more energy-efficient than boilers running on green hydrogen (cf. Figure 7). In the industry, heat pumps are expected to meet low- to medium-temperature (90+°C) heat demand.

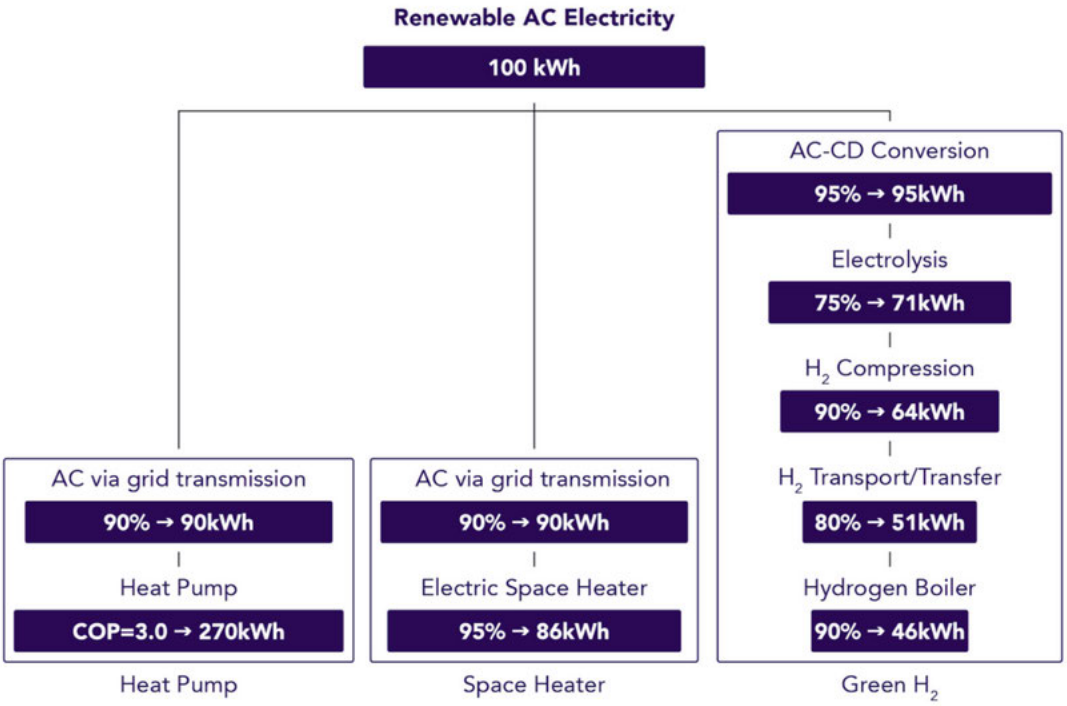

Figure 7 – Heat supply efficiencies. Source: (Hydrogen science coalition, 2023).

There is likewise a large consensus on the necessary ramp-up of **electric mobility** towards 2050 in passenger road transport. Battery electric vehicles are expected to outcompete fuel cell electric vehicles or conventional cars with internal combustion engine, running on synthetic fuels, due to a three to six times higher overall conversion efficiency (Transport & Environment, 2022).

Consequently, **power demand for transport** will strongly increase by a factor of four to eight in the Penta region (cf. Figure 8), reaching a significant part of the domestic power demand in 2050 Penta countries. This growth in decentralised power demand affects not only the need for generation

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[4] Ultimately, the cost-optimal solution should prevail, considering operational costs, notably for energy generation (i.e., generation costs for electricity, hydrogen or synthetic fuels), as well as capital costs, in particular for energy conversion assets (e.g., electrolysers), grid infrastructure, or end-user equipment (e.g., boilers, heat pumps).

capacity (cf. Sections 4.2.2 and 4.2.3), but also the operation and need for distribution grid capacity (cf. Section 4.3.2).

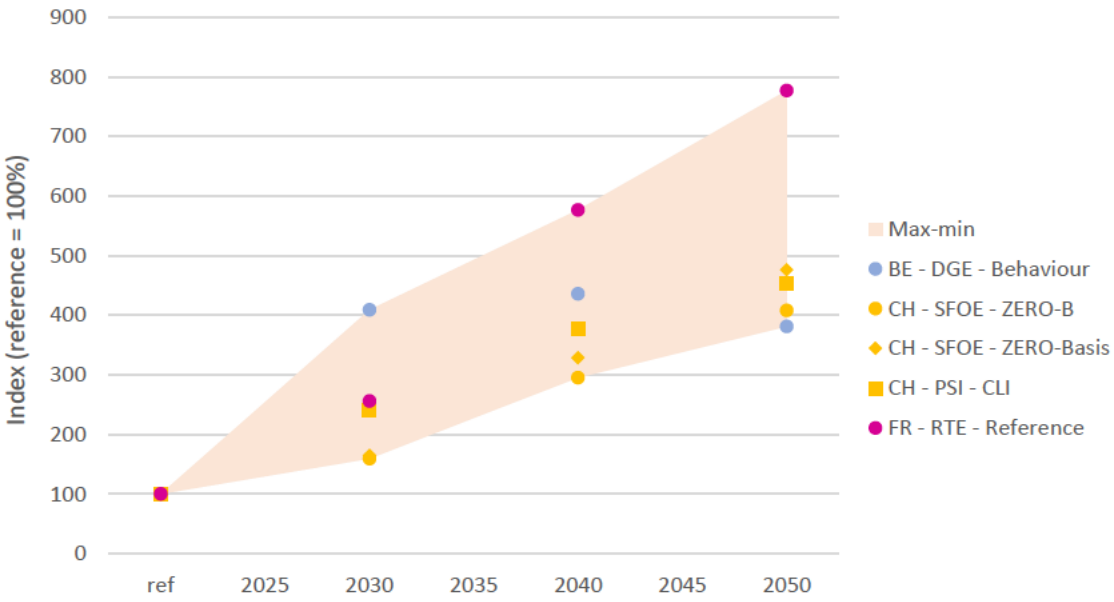

Figure 8 - Evolution of final electricity demand in transport. Source: own illustration.

For instance, in Germany, the power demand of the mobility sector is foreseen to increase from 12 TWh in 2018 to 175 TWh by 2045 (Stiftung Klimaneutralität, Agora Energiewende, Agora Verkehrswende, 2021), which respectively represent 2% and 17% of total power demand (cf. Figure 9).

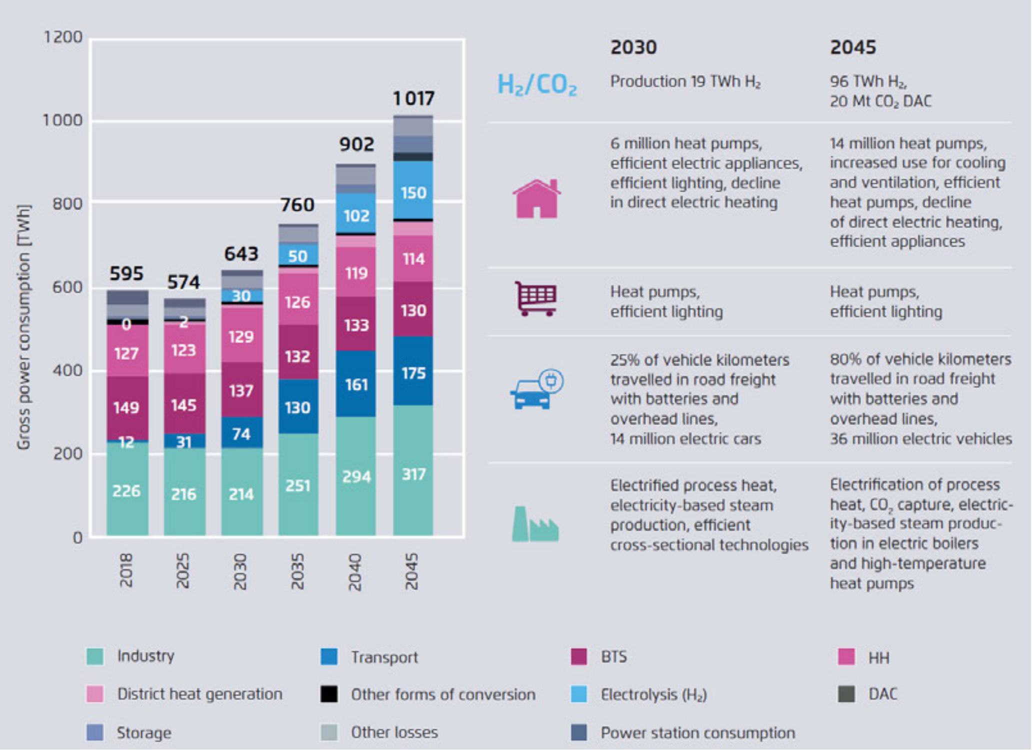

Figure 9 - Evolution of power demand by sector. Source: (Stiftung Klimaneutralität, Agora Energiewende, Agora Verkehrswende, 2021).

The constraints of battery electric vehicles - notably their time of charging and the weight of battery - makes **hydrogen more relevant for specific mobility applications**. For long-distance trucks and coaches, decarbonised hydrogen or synthetic fuels appear as competitors to direct electrification. Long-haul shipping and aviation tend to be **no-regret solutions for hydrogen** (using ammonia or e-fuels). In addition, renewable hydrogen is expected to **replace conventional hydrogen** in existing hydrogen end uses (notably chemical and steel industry, refineries).[5]

4.1.3 Hydrogen demand drives needs for substantial electrolyser investments, with hydrogen imports reducing additional pressure on power systems

As outlined in Section 4.1.1, the increase in future power demand is partially driven by the need to produce renewable (or in some cases low-carbon) hydrogen, which is ensured by electrolysers running on renewable or low-carbon electricity. Across the scenarios investigated, the Penta region is expected to host a **range of 75 GW to 135 GW of electrolysers in 2050**, with 13 GW in 2030 according to national studies. It is to be noted that policy developments are progressing rapidly, and that the latest announcements from France, Germany, the Netherlands and Austria already sum up to a minimum of

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[5] A revision of the Renewable Energy Directive 2018/2001will define targets for the substitution of fossil hydrogen by renewable hydrogen.

20.5 GW in 2030[6]. The TYNDP 2022 projects 117 to 143 GW of installed electrolysis for Austria, Belgium, Germany, France, and the Netherlands by 2050 (ENTSO-E, ENTSOG, 2022). The study published by Elia only expects 40 GW in EU27+3 by 2050 (Elia Group, 2021).

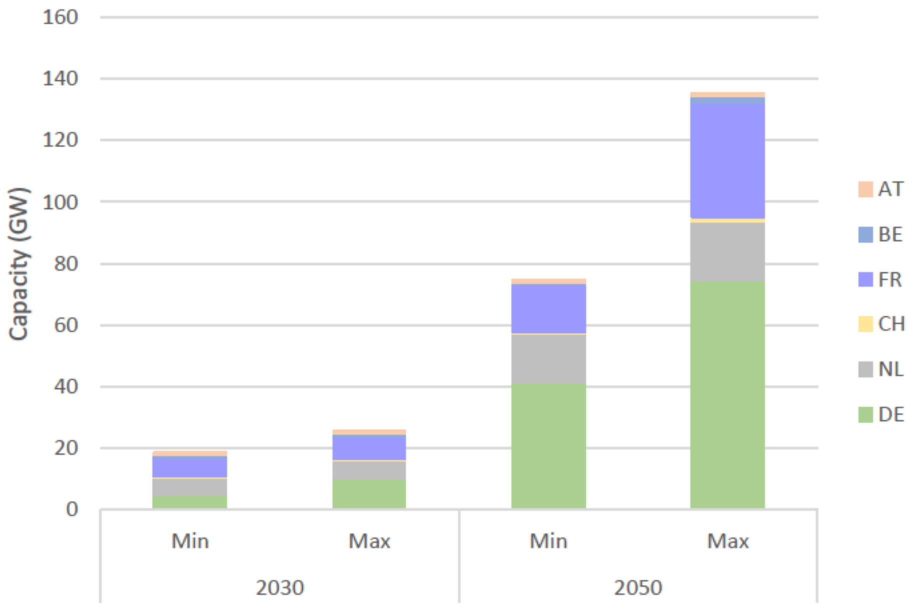

Figure 10 - Electrolyser capacities in the Penta region according to national scenarios. Source: own illustration.

In the majority of the scenarios, **electrolysers are expected to operate with renewable/low-carbon electricity**. Two different operation modes are considered in the analysed scenarios[7]: **Flexible electrolysers** may adapt their operation to price signals (e.g., high wind or solar power production) to ensure not only additionality but also simultaneity of power and hydrogen production. This operation mode brings short to long-term flexibility to the power system and can facilitate the integration of more renewable power production, provided that there is sufficient hydrogen storage available. On the opposite, **base load electrolysers** are considered to operate non-stop, thereby reducing the fixed-cost component in the levelized cost of hydrogen generation. This operation mode may in particular be present in countries with significant low-carbon base load power production assets (namely nuclear or hydro).

In some studies, **offshore renewable energy hubs** are foreseen to produce hydrogen or synfuels offshore which will be directly integrated in the European gas grid. This co-location of electricity and

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[6] 3 to 4 GW were announced by the Netherlands, 10 GW in Germany, 6,5 GW in France, and 1 GW in Austria (IEA, 2022).

[7] See for instance (RTE, 2022), where electrolyser full load hours between flexible and base load operation differ by a factor of two.

hydrogen production implies that domestic hydrogen demand may be met without putting additional stress on the power system.

Hydrogen imports (including its derivatives) are foreseen as a must-have to complement domestic, power-based hydrogen generation, in order to further decarbonise the economies without adding too much pressure on power systems and domestic resources. However, a lot of uncertainties remain in the long-term vision on the order of magnitude, origin[8] and type of energy carrier for hydrogen imports. Few scenarios feature distinct figures on hydrogen import volumes and the figures vary widely. Figure 11 illustrates the ratio between domestic hydrogen supply and hydrogen imports for all scenarios featuring both types of information.

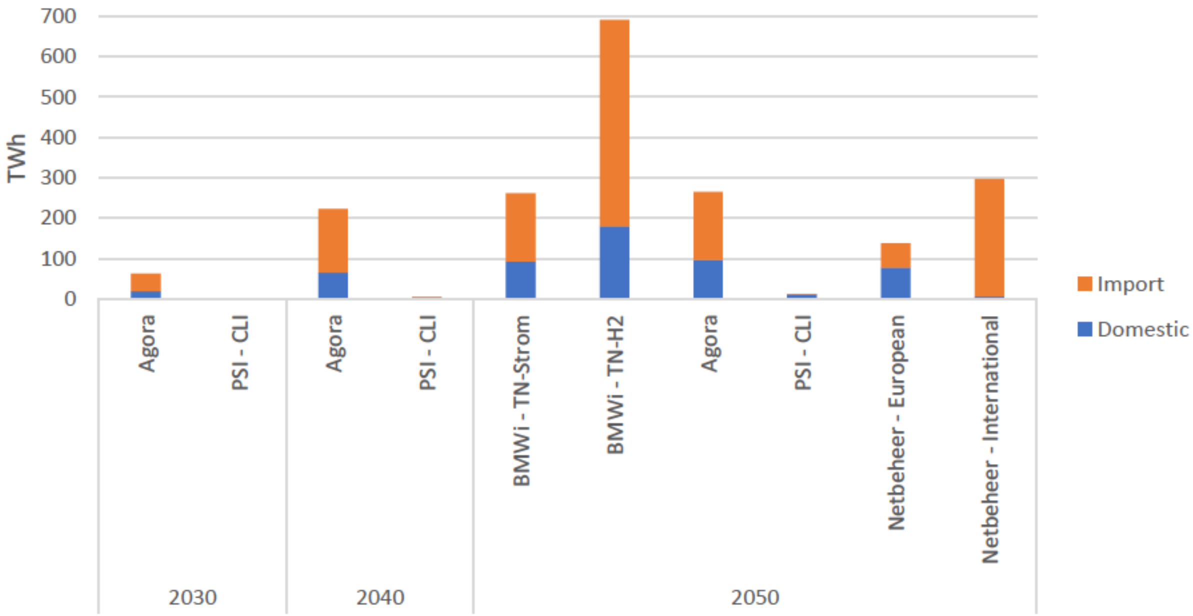

Figure 11 – Hydrogen supply modes (imports versus domestic production) in selected scenarios Source: own illustration.

The most ambitious scenarios in terms of hydrogen development tend to rely more on hydrogen imports. For instance, the increase of hydrogen demand in TN-H2 compared to TN-Strom is mainly borne by imports (BMWi, 2021).

Countries are not endowed with equal solar and wind development opportunities, and areas with more constrained renewable potentials need to rely on imports to larger extents. Domestic power generation potentials may only meet a share of power demand to generate green molecules (i.e. hydrogen and derivatives). This is in particular the case of Belgium, Germany and the Netherlands. In

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[8] The studies and scenarios do not specify in detail the origin of the hydrogen. It may be imported from other EU countries as well as from over-seas.

the case of Belgium, according to the study published by Elia (Elia Group, 2021), the hydrogen demand cannot be met by domestic hydrogen production due to insufficient RES potentials (cf. Figure 12).

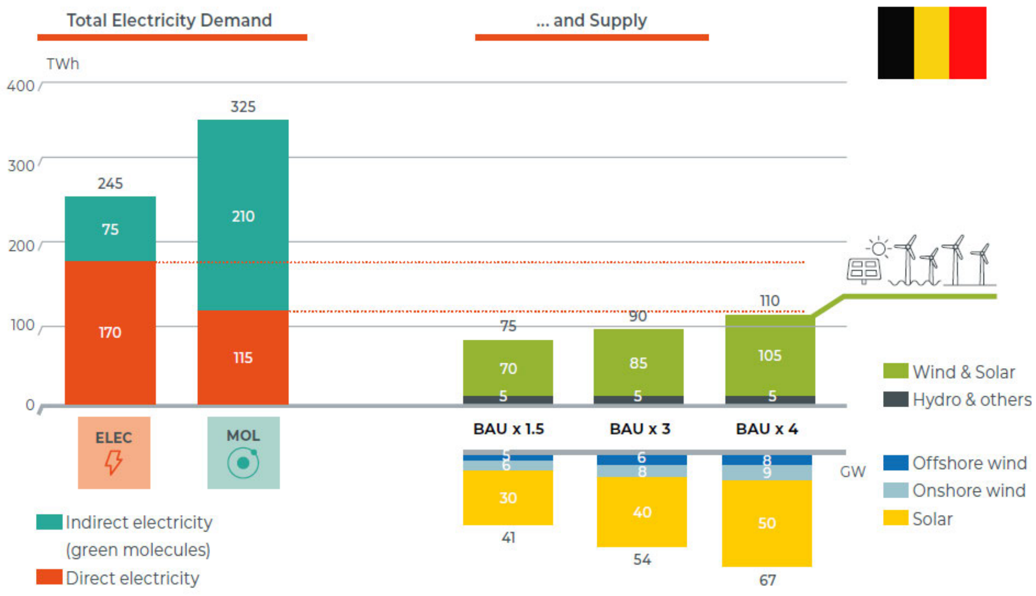

Figure 12 – Belgium projected power balance in 2050, according to two demand scenarios, and three different supply scenarios. Source: (Elia Group, 2021).

4.1.4 Thermal renovation is a precondition to building stock decarbonisation, which cannot rely on heat pumps roll-out only

All the scenarios analysed identify building renovation and heat pumps deployment as a necessary precondition for the decarbonisation of the buildings sector. Heat pumps are indeed the most economical solution for decentralised heat supply in buildings. They operate particularly efficiently at low flow temperature. Building **renovation** (and ambitious standards for new buildings) facilitate **heat pump deployment and avoid over-dimensioning** of heat pumps as well as additional **pressure on the power system.**

According to the Climate Neutral 2045 scenario published by Agora Energiewende for Germany (Stiftung Klimaneutralität, Agora Energiewende, Agora Verkehrswende, 2021), building renovation rates need to increase from 1.5% to 1.75% between 2020 to 2045 (Figure 13). The study of the French TSO (RTE, 2022) even assumes the building renovation to more than double from 1.2%/year in 2020 to 2.0%/year by 2030 and 2.5%/year from 2040 onwards.

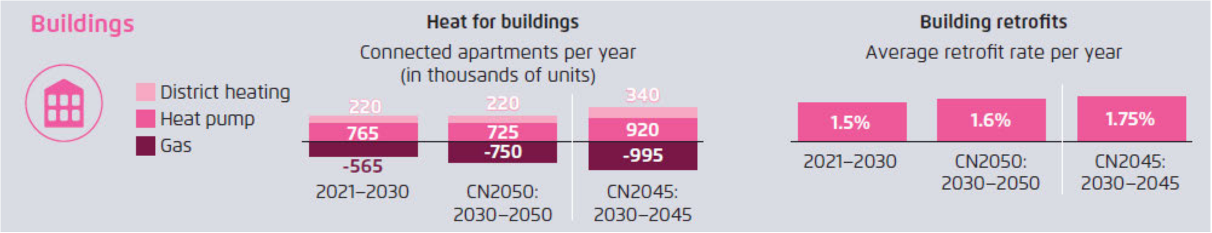

Figure 13 – Heat supply technologies and building renovation rates by year. Source: (Stiftung Klimaneutralität, Agora Energiewende, Agora Verkehrswende, 2021).

The study published by (Elia Group, 2021) considers two distinct scenarios for the decarbonisation of the EU economy, one relying primarily on direct electrification (tagged ELEC) and the other on indirect electrification (i.e., decarbonised molecules, tagged MOL). The assumptions for the share of heat pumps vary in both scenarios: 30% vs 75% for residential buildings, and 45% vs 80% for tertiary buildings, in the MOL vs the ELEC scenario, cf. Figure 14.[9] However, in both scenarios heat demand is expected to drop significantly (60% and 45%, respectively in the two sectors), that is buildings renovation appears to be an imperative necessity.

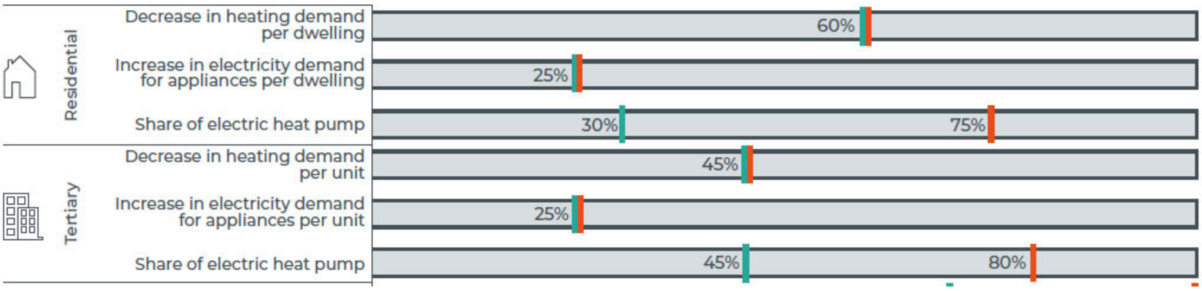

Figure 14 - Evolution of heat demand and supply in EU buildings by 2050 (green bar: MOL scenario, orange bar: ELEC scenario. Source: (Elia Group, 2021).

4.1.5 Demand-side flexibility is key to facilitate system-friendly electrification

The large majority of analysed scenario assessments build upon the assumption that the **electricity consumption of selected existing end-uses and notably new end uses is going to be flexible in the mid- to long-term future**. For instance, in France, half of the additional electricity demand in 2050 is borne by flexible usages, cf. Figure 15 (RTE, 2022).[10] The flexibility potentials related to demand-side flexibility (DSF) represent a major element to meet the increasing flexibility needs that result from rising amounts of renewables in the power system (cf. Section 4.2.3). At the same time, **power demand from new electricity consumers being flexible is a prerequisite to minimize the impacts on power supply and network infrastructure**. The most relevant end uses considered suitable for demand-side flexibility include:

- **Heat pumps** contribute to an increase in power demand (in particular in winter time, when power systems are typically already under stress), but can provide short-term flexibility (in the range of 24 hours) at times of scarce power supply; their load shifting potential varies throughout the year and tends towards zero in summer time (except for reverse heat pumps, generating heat and cooling). Heat storage may increase the flexibility in the operation of

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[9] Heat pumps may be complemented by district heating and biomass.

[10] In the (Agora Energiewende, 2022) study, 64% of the total 2035 power demand consists of conventional, i.e. final power demand. 36% of the total power demand (320 TWh out of the 894 TWh) relate to end-uses with flexible consumption (electrolysis, flexible electric boilers, heat pumps, electromobility and consumption of pumped storage and batteries).

heat pumps[11]. This also applies to large-scale heat pumps that are integrated in district heating networks equipped with heat storage assets.

- **EV deployment** may imply significant capacity challenges if car owners are to charge "intuitively" (e.g., back from the office at 6pm). Flexible EV charging is considered key to keep pressure on power systems manageable[12].
- Flexible operation of **electrolysers** allows for RES integration and power system balancing as hydrogen production may adapt to match RES generation profiles (within the realms of economic profitability and under the prerequisite of available hydrogen storage potentials). (RTE, 2022) considers two modes of operation for electrolysers, one of which is flexible, allowing better integration of variations in power production[13].
- **Industrial load shifting** or shedding is a major source of flexibility among existing electricity consumers.[14] (RTE, 2022) considers an increase in the industrial load shedding potential, as a result of the increased electrification of industry.

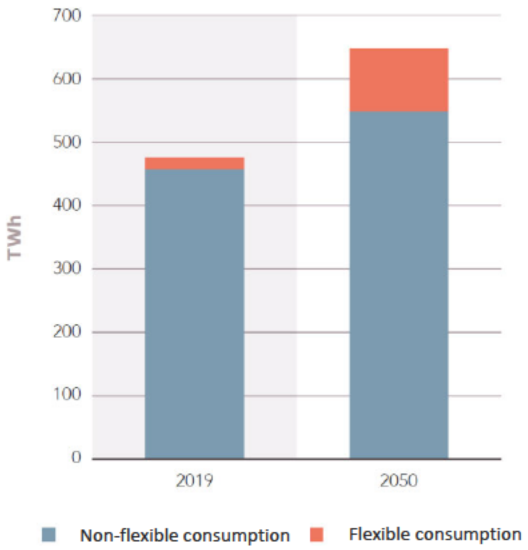

Figure 15 – Share of flexible consumers in total electricity demand in France by 2050. Source: (RTE, 2022).

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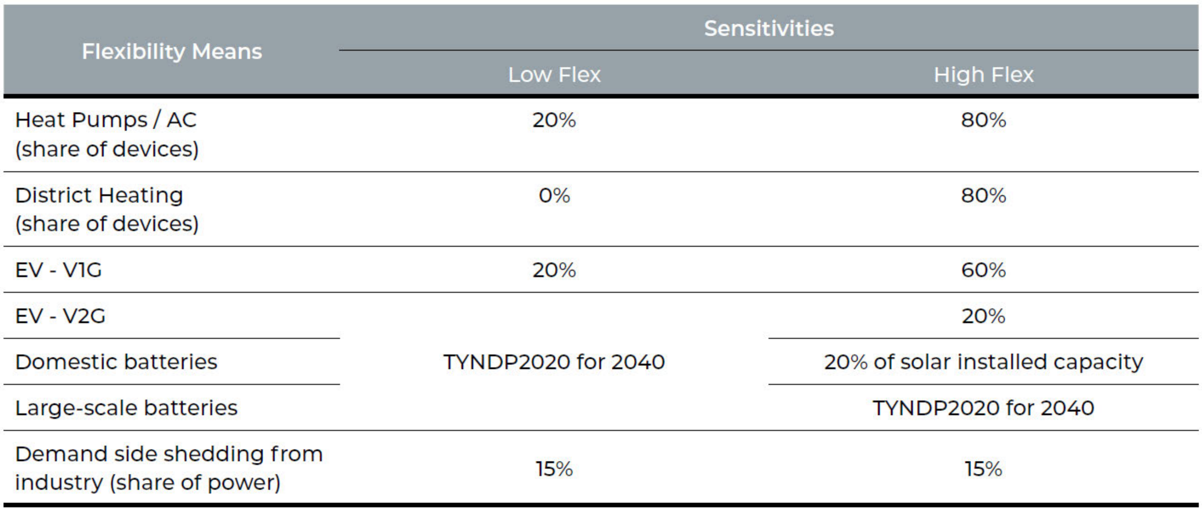
[11] The (Paul Scherrer Institute, 2021) study emphasises the role of heat pumps combined with thermal storage, to provide flexibility to the electricity system. In the CLI scenario, 11% of the total power consumption for residential heating is shifted for the provision of hot water and space heating.

[12] Vehicle-to-grid can also bring further flexibility, see (Agora Energiewende, 2022).

[13] Electrolysers also bring further demand side flexibility in the (Agora Energiewende, 2022) study.

[14] Other existing consumers may likewise provide flexibility to power systems, such as white appliances or electric heaters. However, their contribution is expected to decrease in the future due to efficiency improvements or shifts to alternative technologies.

However, **studies and individual scenarios differ significantly when it comes to the level of DSF deployment** (in terms of “smart” end uses, the consideration of V2G for electric vehicles, and static or dynamic DSF considering static or dynamic time-varying tariffs[15]), as illustrated for instance in Figure 16 for the analysis realised by (Elia Group, 2021).



Flexibility Means	Sensitivities	
	Low Flex	High Flex
Heat Pumps / AC (share of devices)	20%	80%
District Heating (share of devices)	0%	80%
EV - V1G	20%	60%
EV - V2G	TYNDP2020 for 2040	20%
Domestic batteries		20% of solar installed capacity
Large-scale batteries		TYNDP2020 for 2040
Demand side shedding from industry (share of power)	15%	15%

Figure 16 - Flexibility scenario assumptions. Source: (Elia Group, 2021).

The flexibility potential resulting from DSF depends on the actual share of “smart” end users, yet **the technical potential is considered to be very important**. Figure 17 illustrates the DSF potential in terms of capacity and reservoir size, highlighting that the flexibility contribution from heat pumps and EVs (two upper parts of the stacked chart) can exceed the capacities of existing pumped hydro storage by a factor of ten.

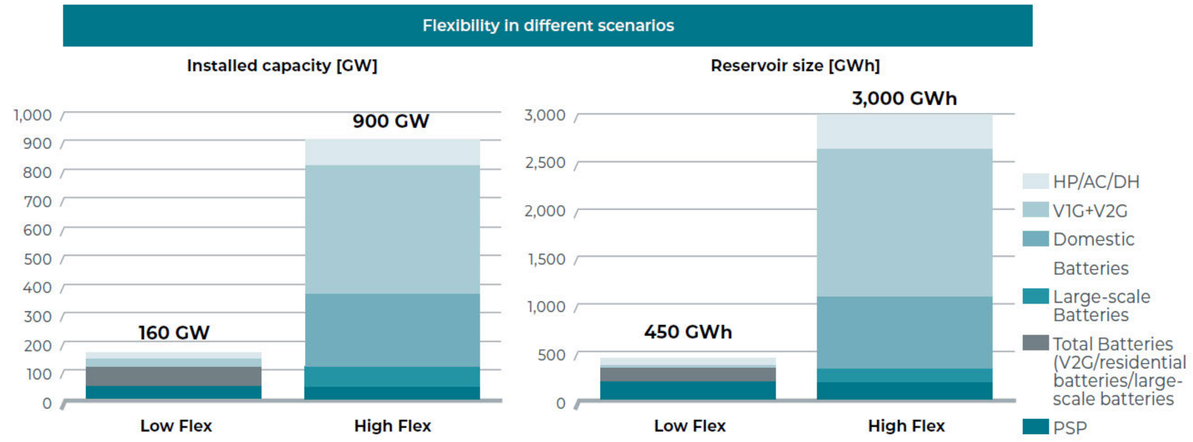


Figure 17 – 2050 EU flexibility potentials in two distinct scenarios. Source: (Elia Group, 2021).

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[15] Static time-varying tariffs correspond to time-of-use tariffs

4.2 The future of electricity supply

The following observations outline major observations regarding the evolution of future power supply and related implications on flexibility needs.

4.2.1 Penta power production is predominantly or fully decarbonised by 2035

There is a shared view among the reviewed scenarios for the Penta countries that the power sector will be **predominantly or fully decarbonised by the year 2035.** All scenarios foresee a decrease of power emission factors below 50 gCO2/kWh by then (which is not the case for the European Commission's Long-Term Strategy), cf. Figure 18.

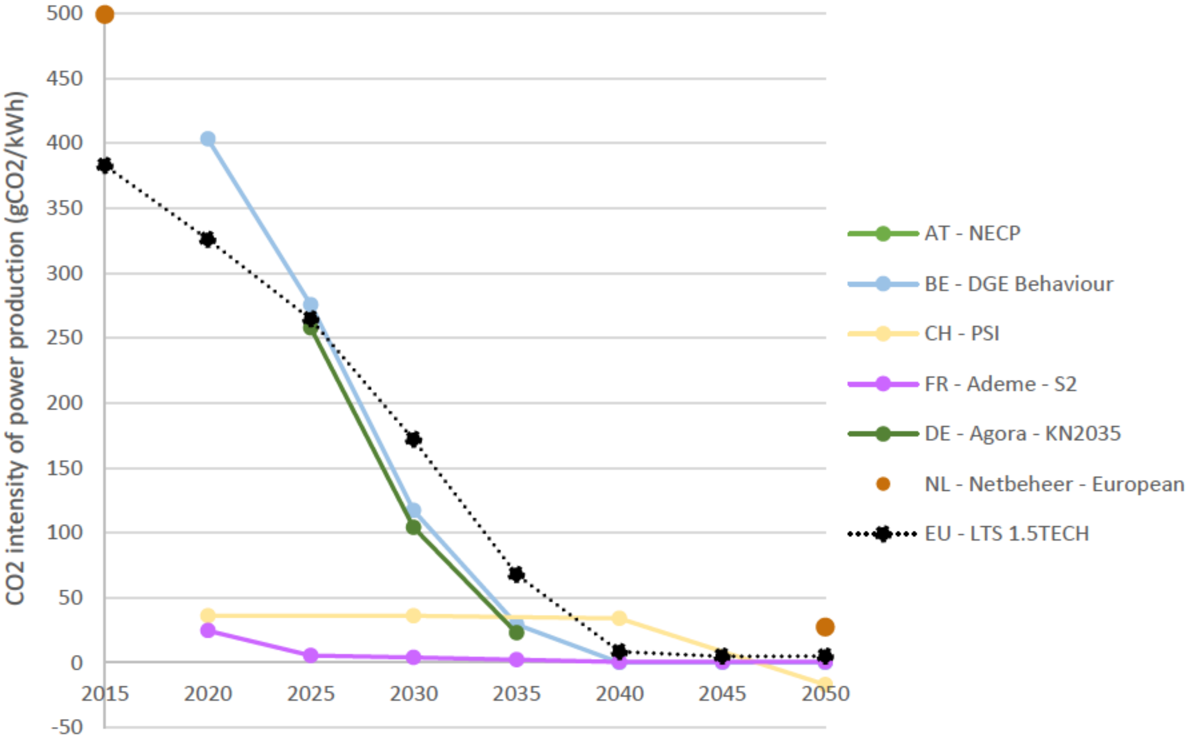

Figure 18 - Evolution of CO2 intensity of power generation for selected scenarios. Source: own illustration.

The required **level of national ambition to drive down emissions depends obviously on the current composition of the power generation mix** and the related carbon intensity. These intensities range from less than 100 gCO2/kWh, for countries like France or Switzerland, to more than 400 gCO2/kWh for countries like Belgium, Germany or the Netherlands.

The majority of scenarios settle at around a net-zero emission factor by 2050 and only very few specific scenarios aim for **negative carbon emissions from the power system** in order to reach system-wide net-zero. These negative emissions are achieved through biomass-fuelled power production and CCS (BECCS), and are expected to materialise towards the end of the time horizon studied (2020 - 2050) only. For instance, the CLI scenario for Switzerland (Paul Scherrer Institute, 2021) assumes negative emissions amounting to 0.8 Mt in 2050, thanks to the production of electricity from wood and waste, combined with CCS.[16]

4.2.2 Massive vRES deployment in all scenarios

The share of electricity produced by variable renewable energy sources (vRES), that is wind or solar PV, will reach 10% to 70% of national production volumes by 2030 and 39% to 95% by 2050 (cf. Figure 19), i.e. vRES will be the main source of power generation in most scenarios by 2050.

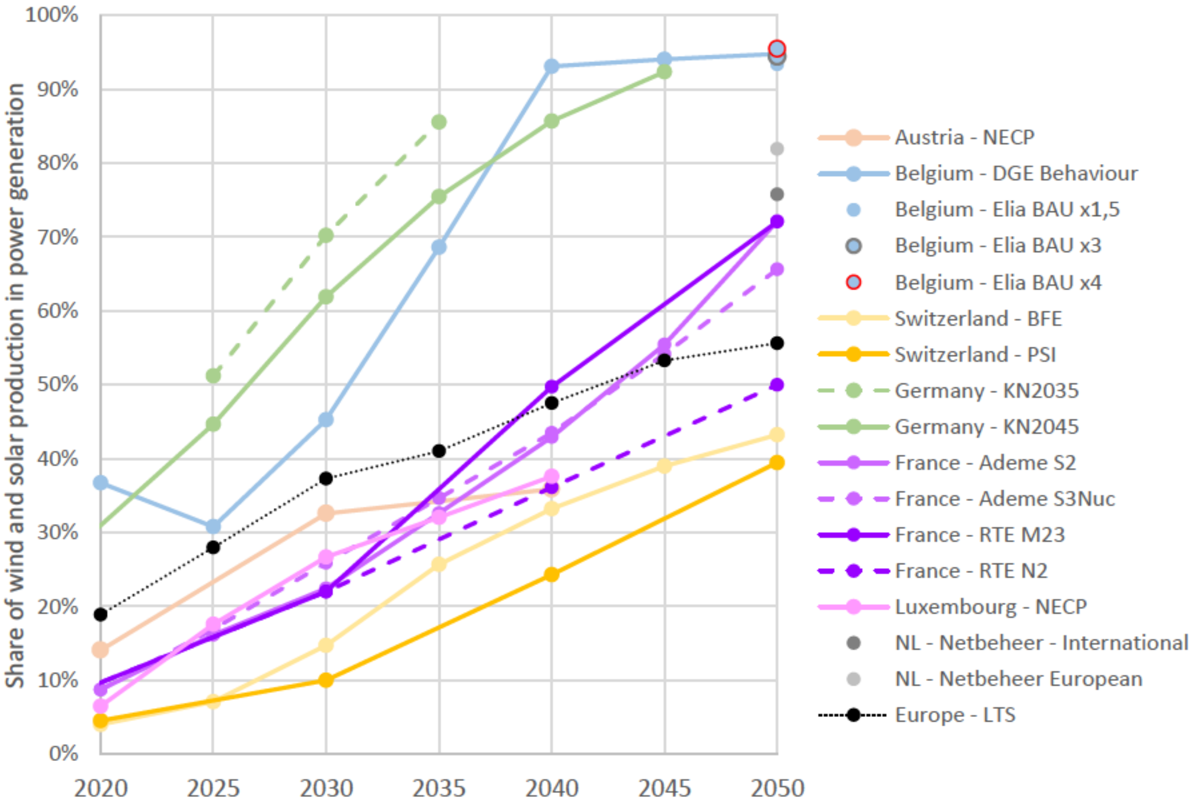

Figure 19 - Share of vRES in power generation for selected, particularly ambitious scenarios[17]. Source: own illustration.

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[16] The second chapter of the IPCC notes already in 2018: "All analysed pathways limiting warming to 1.5°C with no or limited overshoot use CDR to some extent to neutralize emissions from sources for which no mitigation measures have been identified and, in most cases, also to achieve net negative emissions to return global warming to 1.5°C following a peak (high confidence). The longer the delay in reducing CO2 emissions towards zero, the larger the likelihood of exceeding 1.5°C, and the heavier the implied reliance on net negative emissions after mid-century to return warming to 1.5°C (high confidence)." (Rogelj, Shindell, & al., 2018)

[17] The scenarios included are the Zero Basis scenario for Switzerland (Bundesamt für Energie BFE, 2021), the NECP for Austria (Austrian Federal Ministry for Sustainability and Tourism, 2019) and Luxembourg (Luxembourg

The total amount of installed capacities reaches around 250 GW of solar PV by 2030 and close to 750 GW by 2050 in the Penta region according to the more ambitious scenarios (cf. Figure 20). Wind onshore and offshore capacities are expected to represent 240 GW and 150 GW by 2050, respectively.

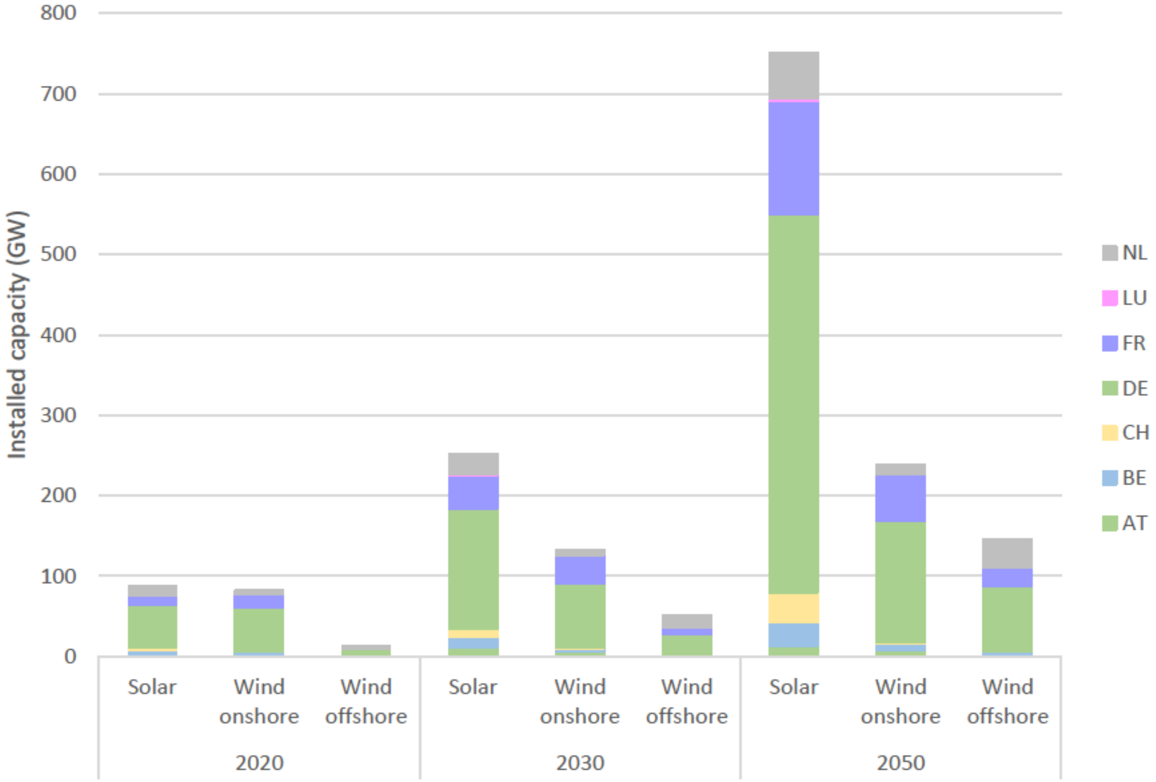

Figure 20 - Evolution of installed capacity (GW) in specific ambitious scenarios. Source: own illustration[18].

Achieving such a high level of vRES penetration requires unprecedented deployment rates. According to the scenarios analysed, annual installation rates at the Penta level need to double for solar PV and wind offshore in the current decade (2020-30) compared to the previous one, and must even further

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Ministry of the Environment, Climate and Sustainable Development, and Luxembourg Ministry of Energy and Spatial Planning, 2018), the S3 Nuc scenario from the Ademe Study for France (ADEME, 2021), the Climate Neutral 2035 (Agora Energiewende, 2022) and the Climate Neutral 2045 (Stiftung Klimaneutralität, Agora Energiewende, Agora Verkehrswende, 2021) scenarios for Germany, the Elia study (Elia Group, 2021) and the Behaviour scenario from the DGE study (DG Environment, 2021) for Belgium, the European Scenario from the Netbeheer study for the Netherlands (Netbeheer, 2021) and the Long Term Strategy for Europe (European Commission, 2018).

[18] Based on the following scenario selection: NECP (Austrian Federal Ministry for Sustainability and Tourism, 2019) for Austria, Behaviour scenario from (DG Environment, 2021) for Belgium, (Stiftung Klimaneutralität, Agora Energiewende, Agora Verkehrswende, 2021) for Germany, S3 scenario from (ADEME, 2021) for France, Zero Basis scenario from (Bundesamt für Energie BFE, 2021) for Switzerland, the Target scenario from (Luxembourg Ministry of the Environment, Climate and Sustainable Development, 2021) for Luxembourg and European scenario from (Netbeheer, 2021) for the Netherlands.

accelerate afterwards in order to cope with the rising electricity demand and the retrofitting of existing plants that reach the end of their technical lifetime[19], cf. Figure 19.

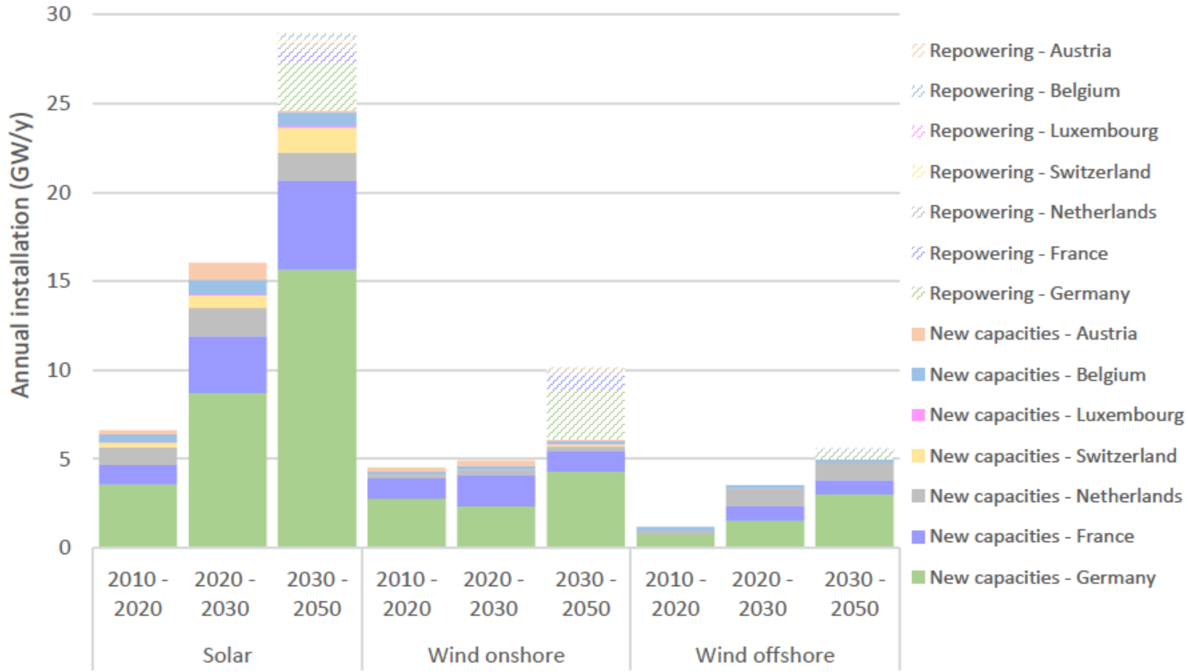

Figure 21 - Evolution of annual vRES installation rates (GW/y)[20]. Source: own illustration.

Renewable energy sources will be complemented by **other low-carbon power generation technologies**, namely hydro (e.g., in Austria and Switzerland) and nuclear (notably in France and Switzerland[21]). Carbon capture and storage (CCS) does not play a role in the future power mix of the Penta countries (except in the context of negative emissions, in combination with bioenergy, cf. Section 4.2.1). However, some scenarios consider the use of more immature technologies like small modular nuclear reactors, e.g. the N03 scenario of (RTE, 2022).

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[19] The repowering rates are based on the 2020 wind and solar installed capacities. The calculation assumes that these capacities are fully repowered over the period 2030 – 2050.

[20] Based on the following scenario selection: NECP (Austrian Federal Ministry for Sustainability and Tourism, 2019) for Austria, Behaviour scenario from (DG Environment, 2021) for Belgium, (Stiftung Klimaneutralität, Agora Energiewende, Agora Verkehrswende, 2021) for Germany, S3 scenario from (ADEME, 2021) for France, Zero Basis scenario from (Bundesamt für Energie BFE, 2021) for Switzerland, the Target scenario from (Luxembourg Ministry of the Environment, Climate and Sustainable Development, 2021) for Luxembourg and European scenario from (Netbeheer, 2021) for the Netherlands.

[21] There are no new nuclear power plants planned in Switzerland. The last existing nuclear power plant will go offline by 2034.

4.2.3 The need for flexibility will increase significantly

Rising shares in power production from variable renewable power generation but also the integration of new power consumers with distinct load profiles will significantly increase the need for power system flexibility at all timescales in order to balance electricity demand and supply at any moment and to ensure a stable and reliable power system. Figure 22 illustrates the cumulated flexibility needs of all Penta countries at the daily, weekly and seasonal timescale for three different power mix scenarios.[22] It is common to all scenarios that in particular daily and weekly flexibility needs will at least double by 2030, compared to current values, and more than quadruple by 2050. In individual countries of the Penta region, the increase in daily flexibility needs may increase by a factor of five to six. Seasonal flexibility needs tend likewise to increase but to a more limited extent (<+200% by 2050).

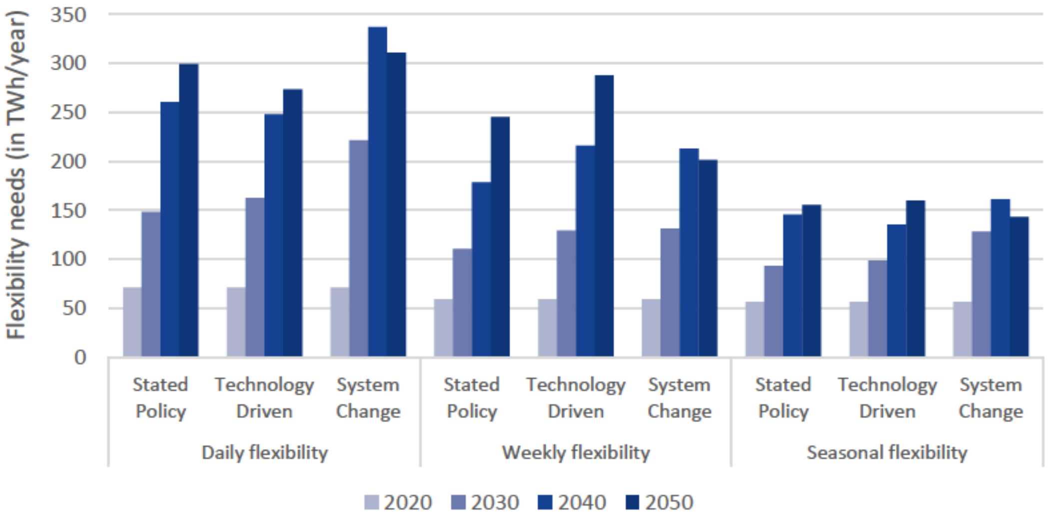

Figure 22 - Cumulated flexibility needs of Penta countries for the three different scenarios analysed[23], 2020 to 2050. Source: (Trinomics, Artelys, 2023).

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[22] The flexibility needs were quantified by Artelys in the context of a parallel study, in cooperation with Trinomics and on behalf of the Pentalateral Energy Forum. The entire analysis is available under the following reference: (Trinomics, Artelys, 2023). Flexibility needs are assessed by analysing the dynamics of the residual load (i.e. the total load less the production from vRES). Daily flexibility needs are defined as the difference between the hourly residual load throughout a day and its daily average. The result is expressed as a volume of energy per day (e.g. GWh/day). Summing up these daily (positive) differences over all 365 days of the year reveals the overall daily flexibility needs (expressed in GWh or TWh per year) one may respond to in order to obtain a residual load that is flattened out on a daily basis. Weekly and annual needs are calculated by determining and aggregating the difference between the daily and the weekly average, and the weekly and the annual average, respectively.

[23] The three scenarios used for the analysis originate from the study by (New Generation, Ember, 2022). The Stated Policy pathway is aligned with stated national policies until 2035. The other two pathways (Technology Driven and System Change) are computed to minimise costs while remaining within a carbon budget compatible with the Paris Agreement climate goals. The latter two pathways expand clean electrification, but differ in their assumptions about available technologies and the levels of energy savings resulting from societal change, with the System Change scenario featuring a peaking annual power demand by 2040.

Sub -hourly flexibility needs will rise due to higher amounts of variable power generation from solar PV and wind, being subject to forecast errors (even though forecasting quality continuously improves). Flexibility needs at the daily timescale are triggered by increasing PV shares, given the concentration of power production to midday-hours, ultimately implying a drop in the daily residual load. (cf. Figure 23). But also new power consumers, such as electric vehicles, raise flexibility needs as they increase the evening load peak if not charged in a system-friendly manner.

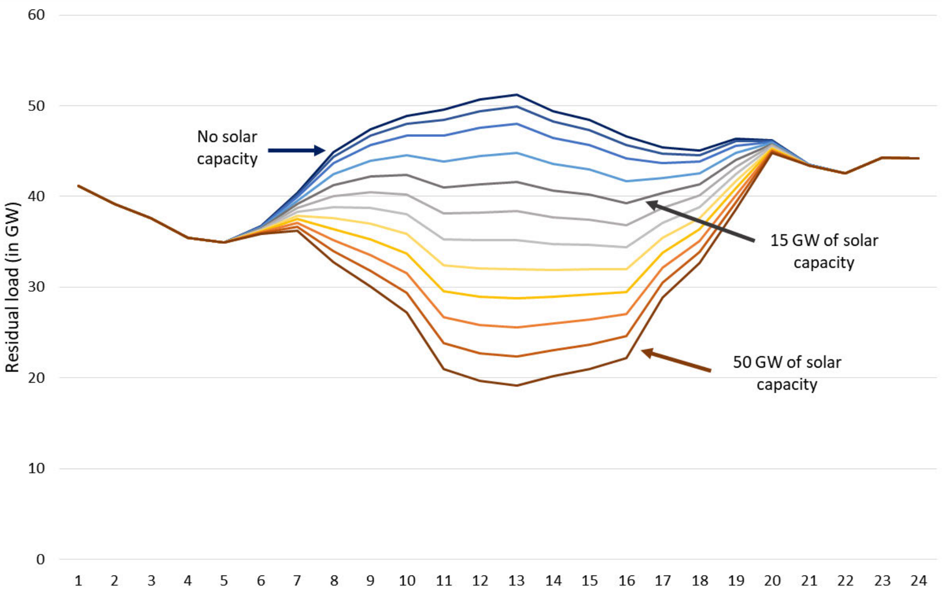

Figure 23 - Illustration of the impact of solar capacity deployment on the residual load in 2030 France (for illustrative purpose). Source: (Artelys, 2017).

The increase in weekly flexibility needs is primarily driven by higher wind penetration levels (with wind regimes featuring rather daily than hourly patterns). The increase in seasonal flexibility needs is linked to an increase in thermo-sensitive power demand (due to heat pump roll-out), while seasonal generation patterns of PV and wind tend to level-out each other (depending on the respective volumes), cf. Figure 24.

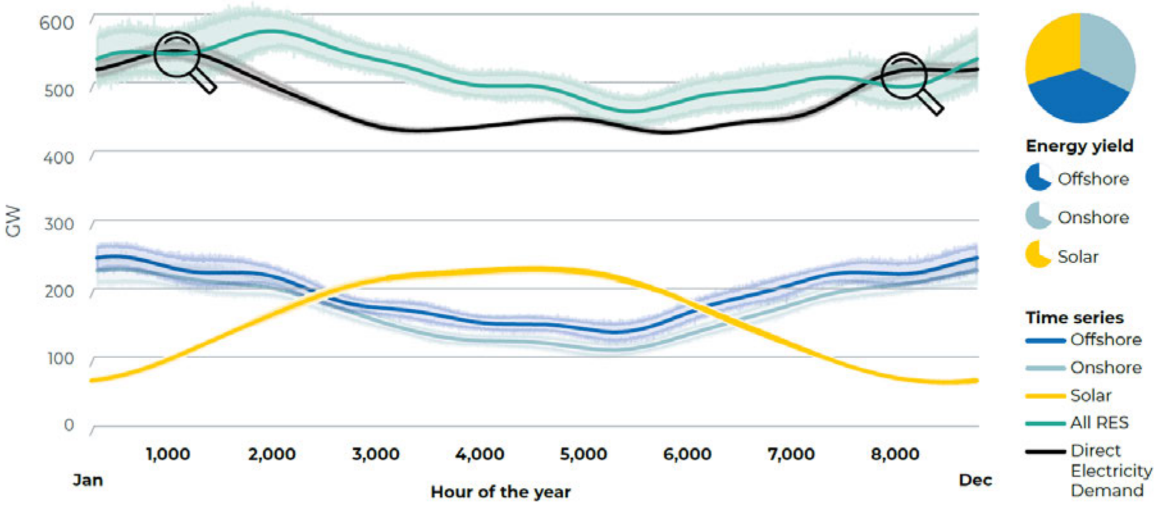

Figure 24 - Seasonal pattern of electricity generation and demand. Source: (Elia Group, 2021).

4.2.4 Regional cooperation as key lever for a least-cost energy system transformation

Across all scenarios, cross-border electricity exchanges play a significant role. In most Penta countries, **power demand is met to a significant extent by electricity imports**. Figure 25 illustrates the share of imports in national power supply. Imports may come from other Penta countries, as well as other EU and non-EU countries. The level of imports (and exports in the case of France in particular) strongly varies across the different scenarios, but typically exceeds current levels of cross-border exchange (requiring additional cross-border capacities, cf. Section 4.3.4).

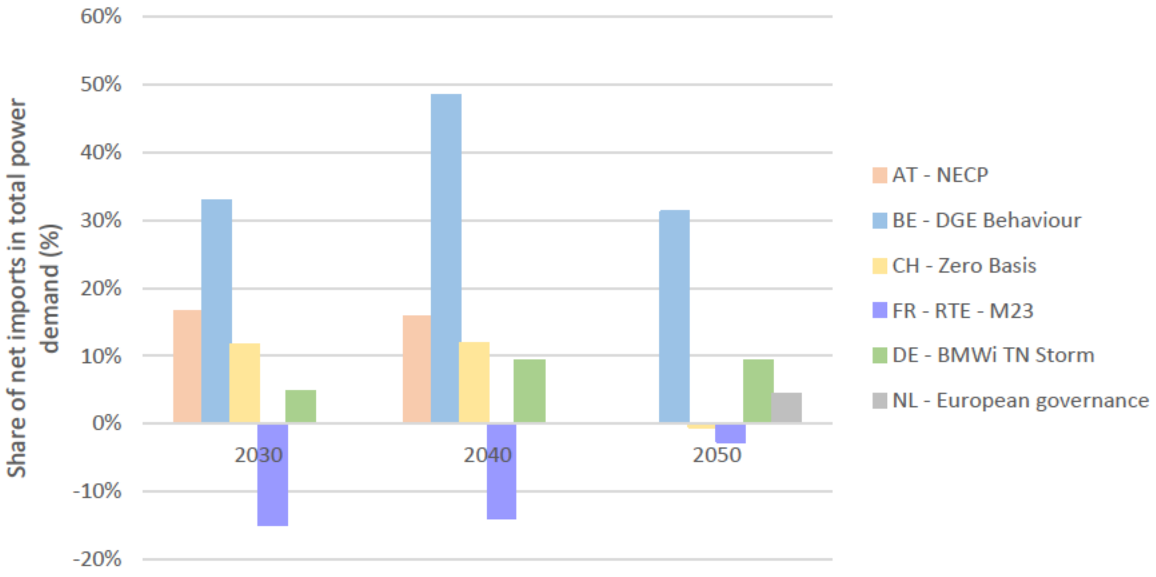

Figure 25 – Share of net imports in total power demand, for ambitious scenario in terms of renewable deployment.[24] Source: own illustration.

Cross-border exchanges help to meet production deficits (e.g., in the case of Belgium). Regional cooperation between Penta countries (but also with other EU and non-EU countries) is key to mitigate the uneven distribution of renewable potentials. Germany and France are the countries offering the highest vRES potentials. In proportion to national power demand, the highest renewable potentials are found for wind power in France and in the Netherlands, cf. Figure 26. Consequently, the projected variation in solar and wind penetration is significant across countries[25].

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[24] NECP for Austria (Luxembourg Ministry of the Environment, Climate and Sustainable Development, and Luxembourg Ministry of Energy and Spatial Planning, 2018), Behaviour scenario for Belgium (DG Environment, 2021), Zero Basis scenario for Switzerland (Bundesamt für Energie BFE, 2021), M23 scenario for France (RTE, 2022), TN-Strom scenario for Germany (BMWi, 2021), International scenario for the Netherlands (Netbeheer, 2021). Data for Austria is not available for the time beyond 2040. Data for the Dutch scenario is only available for the year 2050.

[25] For example, the share of wind generation in Switzerland's power production equals 1% and 5% in 2030 and 2050, respectively, (Zero Basis scenario from (Bundesamt für Energie BFE, 2021)), while its penetration reaches 27% and 54% in 2030 and 2050 in Belgium in the DGE Behaviour scenario (DG Environment, 2021).

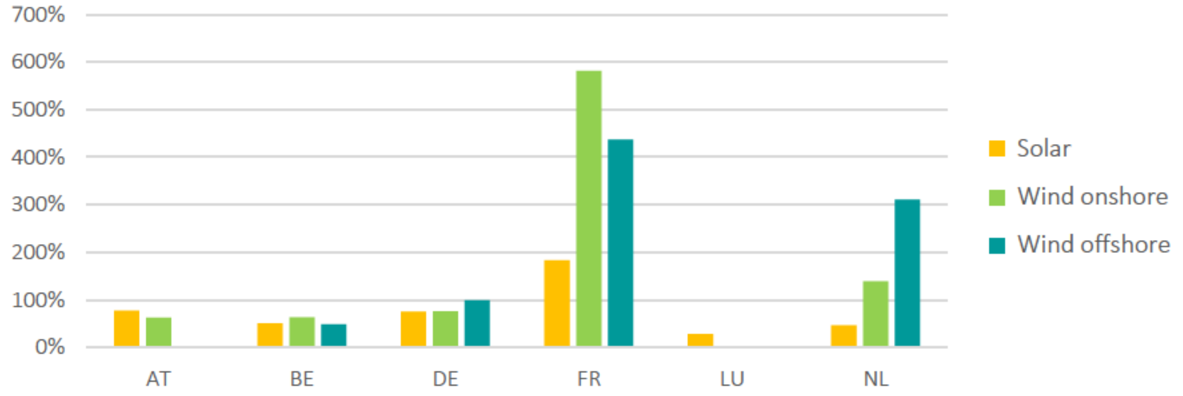

Figure 26 - Technical wind and solar production potentials across Penta countries (excl. Switzerland) compared to 2020 final power consumption. Source: own illustration based on (JRC, 2021) for technical RES potentials, (IEA, 2023) for final power consumption data.

In addition, **cross-border electricity exchanges enable the balancing of national power systems** and contribute to system stability. This is for instance illustrated in Figure 27. Imports meet above-average power demand in winter time (partially driven by the electrification of the buildings sector through heat pump deployment), while exports allow to transport excess renewable energy production to neighbouring countries in summer periods.

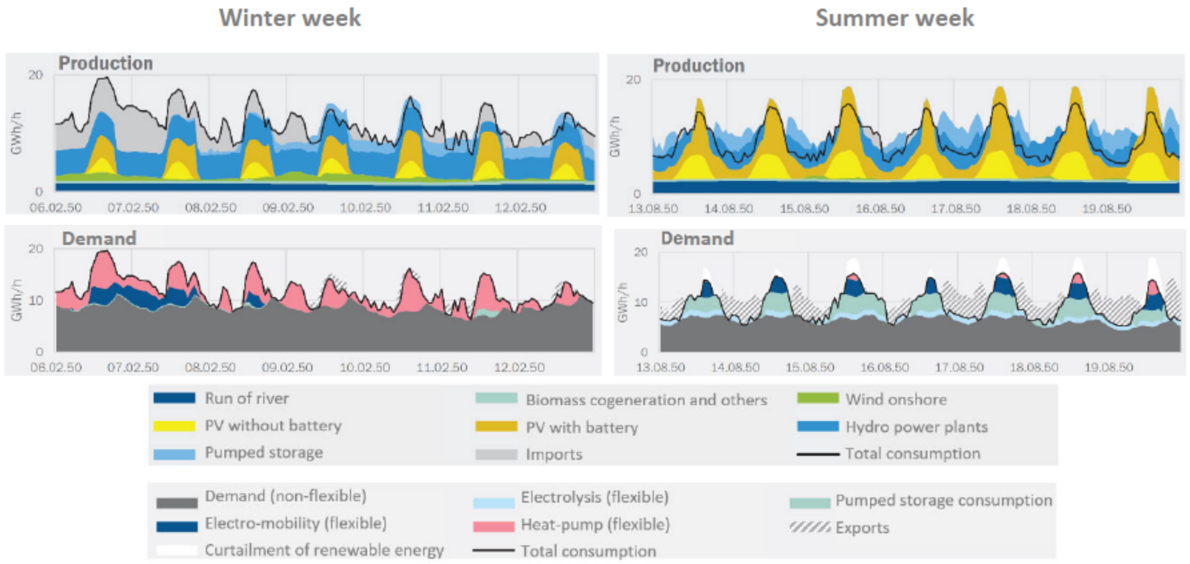

Figure 27 - Hourly supply/demand equilibrium in a representative winter/summer week in 2050 Switzerland (ZERO-Basis scenario). Source: (Bundesamt für Energie BFE, 2021).

The interconnection of power systems ultimately allows to level out variation in vRES power generation as well as in demand patterns, thereby **driving down the needs for additional system flexibility**. Figure 28 illustrates that the increase in flexibility needs (cf. Section 4.2.3) may be lowered by roughly 10% if the Penta countries would be fully interconnected (copper plate) compared to a situation where each country would balance out hourly supply and demand curves at a national level.[26]

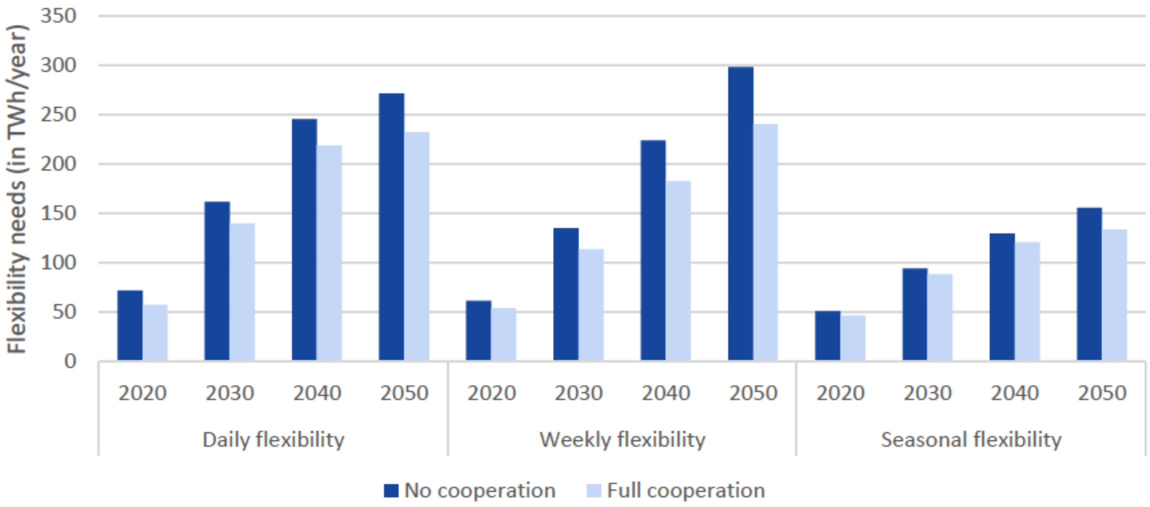

Figure 28 - Impact of regional cooperation on the European flexibility needs. Source: (Trinomics, Artelys, 2023).

Ultimately, **regional cooperation in the deployment of renewable resources may bring down the cost of their integration and of power (and hydrogen) generation**. Siting production technologies in areas where they feature significantly higher load factors is key to cost efficiency. A concerted approach allows to jointly exploit the most favourable RES sites across the Penta region. A coordination approach of renewable deployment also allows to decrease the need for flexibility on all time scales and to minimize infrastructure investments (cf. Section 4.3.5).

Yet, regional cooperation is not only beneficial when it comes to the operation of power systems. At the European level and in Penta countries, the demand for hydrogen produced by electrolysis is expected to increase considerably (cf. Section 4.1.3). Hydrogen production potentials by electrolysis are expected to be insufficient to meet the growing demand. **The cross-border exchange of hydrogen and hydrogen derivatives may help Penta countries to meet future hydrogen demand** and to exchange energy in a more efficient way then via power lines. The Agora Climate neutral 2045 study (Stiftung Klimaneutralität, Agora Energiewende, Agora Verkehrswende, 2021) estimates the need for import of renewable hydrogen in 2030 Germany at 44 TWh of hydrogen, which equals about 70% of

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[26] Figure 28 considers only full cooperation among Penta countries, disregarding exchanges with other neighbouring countries. The impact of European cooperation would be even higher when also the rest of Europe would be considered.

total domestic demand. International potentials are expected to be sufficient to meet these import needs.[27]

(Artelys, 2021) determined the cost of hydrogen, if EU countries were supposed to meet 2030/35 hydrogen demand domestically or by relying on neighbouring countries. Hydrogen generation costs decrease by more than 25%, and national supply cost divergence across countries tends to decrease, as electrolyser investments drop by 20% and make use of cheaper electricity (as they are sited in countries with high-performance RES).

4.3 Power system stability: the role of storage and grids

Section 4.2.3 highlighted the rising flexibility needs of future power systems. Demand-side flexibility and regional cooperation may help to lower the increase in flexibility needs (cf. Sections 4.1.5 and 4.2.4). Low-carbon power generation technologies, referred to in Section 4.2.2, may contribute to meet the remaining needs, next to storage and power grids. The following observations refer notably to the role of storage and grids and their role in the future power system.

4.3.1 Energy storage development is key to ensure adequacy in the Penta region

The development of infrastructures for energy storage is crucial in the Penta region. These developments will help to ensure adequacy in Penta power systems, on various time scales, and should be made in coordination with other flexibility sources.

First, power storage is key to ensure adequacy from short to long term horizons, thanks to battery storage, and pumped hydro storage capacities. The extensive deployment of **hydro resources reduces system costs**. Up to 9 GW of additional reservoirs, run of river and pumped hydro storage capacities, are expected in the Penta region by 2040. This equals an 8% increase compared to the current capacities, according to the Distributed Energy scenario of the TYNDP 2022 (ENTSO-E, ENTSOG, 2022). It is important to note, though, that pumped hydro storage potentials are unevenly distributed across Penta countries, with major capacity extensions materialising in Austria, Switzerland, France and Germany (cf. Figure 29).

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[27] The renewable energy potentials of EU Member States are estimated to be sufficient to meet the future hydrogen demand in the EU (towards 2050). However, this implies significant investments in RES capacities which may raise acceptance issues and implies that several countries (e.g., Germany and Belgium) aim to establish trans-continental hydrogen cooperations already today.

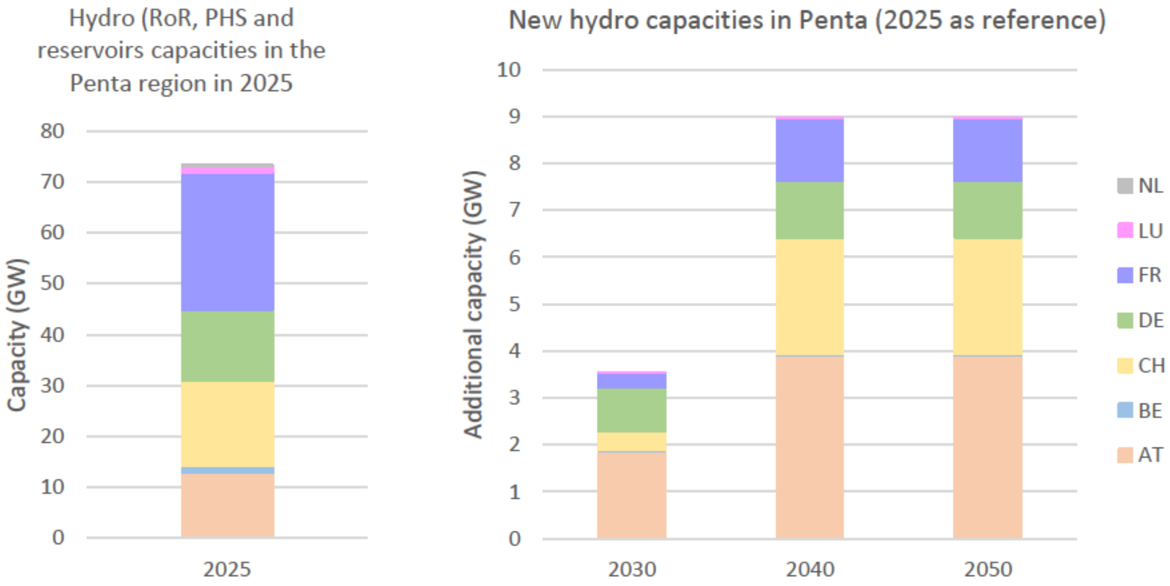

Figure 29 - Projected hydro capacity deployment within Penta. Source: Own illustration based on the TYNDP Distributed Energy scenario from (ENTSO-E, ENTSOG, 2022), TYNDP National Trend scenario from (ENTSO-E, ENTSOG, 2022) used as a reference for 2025.

Battery storage is key for the short-term adequacy of power systems. Around 30 GW of battery storage capacity and 10 TWh of related power output volumes (stationary batteries and prosumer battery, excl. V2G) are expected to be deployed in 2030 within the Penta countries by the TYNDP 2022 Global Ambition scenario, cf. Figure 30. By 2050, capacities will more than double to 72 GW, with a related power output volume of 41 TWh.

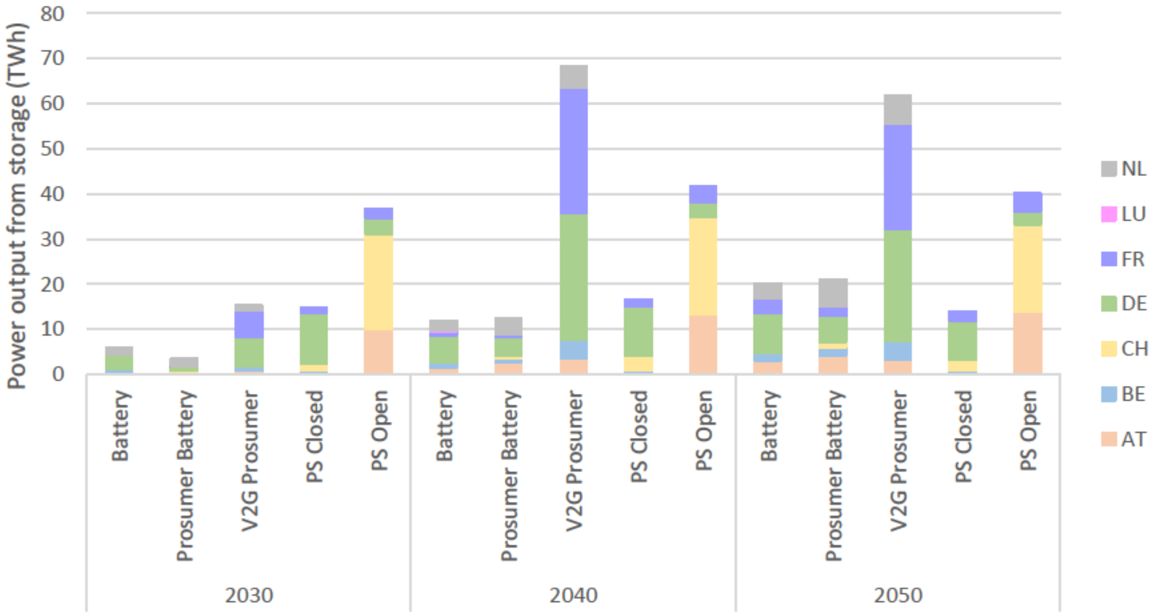

Figure 30 - Power output from storage (TWh). Source: TYNDP Global Ambition scenario from (ENTSO-E, ENTSOG, 2022).

These **power storage technologies compete with other flexibility solutions** such as flexible power generators, cross-border interconnection and demand side flexibility. In particular the smart charging of electric vehicles, vehicle-to-grid (V2G) and smart heat pumps may significantly reduce the need for stationary batteries.

The **electrification of heat unlocks additional storage potentials to support the power system**, namely due to dedicated **heat storage assets** and the thermal inertia of buildings. Thermal storage is thus set to play an increasing role, as shown by the Figure 31 (Paul Scherrer Institute, 2021). These thermal storages can be either linked to decentralised heat supply, namely local storage linked to heat pumps, or to centralised heat supply assets as part of district heating systems, the latter potentially incorporating cogeneration plants. Heat storage enables a flexible operation of electricity-fuelled heat supply assets (notably heat pumps, but also electric resistance heaters). This includes the opportunity of injecting excess renewable power generation into heat systems instead of curtailing the renewable electricity surplus. In addition, heat storage allows cogeneration plants (CHP) to optimally meet electricity and heat demand (if power and heat production can be decoupled[28]) by filling heat storages at times of low electricity demand (or prices) and favour electricity production during high electricity demand/price periods (maintaining a continuous heat supply thanks to the heat storage).

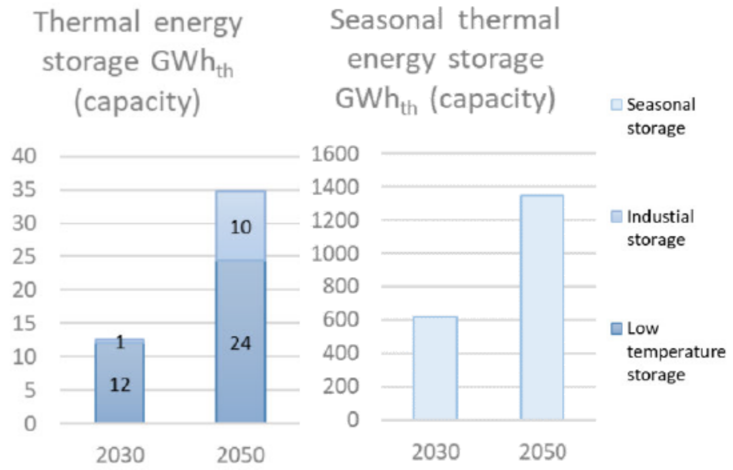

Figure 31 – Capacity (in GWh_th) from thermal energy storage solutions in the CLI Swiss scenario. Source: (Paul Scherrer Institute, 2021).

Hydrogen storage allows for a decoupling of hydrogen production from variable RES-fuelled electrolysers and a specific hydrogen consumption profile. Hydrogen storage further enables the **seasonal storage of electricity via power-to-gas-to-power (P2G2P)**, by converting surplus RES electricity into hydrogen (e.g., during summer), which is then stored and released in winter to be

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[28] Back pressure turbines feature a constant power-heat output ratio, whereas the ratio is variable (in a given range) for extraction-condensing turbines.

reconverted into electricity (via hydrogen turbines or fuel cells). In the INNOV scenario of the PSI study for Switzerland (Paul Scherrer Institute, 2021), about a quarter of the produced hydrogen from electricity is stored and seasonally shifted from summer to winter in 2050, in order to balance the system. The TN-Strom and TN-H2 scenarios respectively foresee a need for 47 TWh and 73 TWh of hydrogen storage[29] (41 and 74 GW of electrolysis) in Germany by 2050 (BMWi, 2021).

However, **hydrogen underground storages are unevenly distributed across Penta countries** (salt caverns are notably located around the Baltic and Nordic Sea basin). Cooperation is needed to jointly exploit them, as well as a joint planning approach to develop transport infrastructures to connect them to production and consumption sites (cf. Section 4.3.5).

4.3.2 Decentralised electricity production and use drive need to reinforce distribution grids

Decentralised solar and wind generation capacities are mostly connected to distribution grids. The **significant increase in vRES deployment will thus imply a tangible rise in power generation capacities being connected to distribution grids** (in contrast to conventional, centralised power plants being connected to the transmission grid). In France, where about 80% of RES capacities (excl. wind-offshore) are connected to the distribution grid level, solar and wind capacities connected to distribution grids are expected to rise by a factor of more than 5, to more than 160 GW (according to the M23 scenario of (RTE, 2022), cf. Figure 32. This implies that distribution networks need to be extended and reinforced.

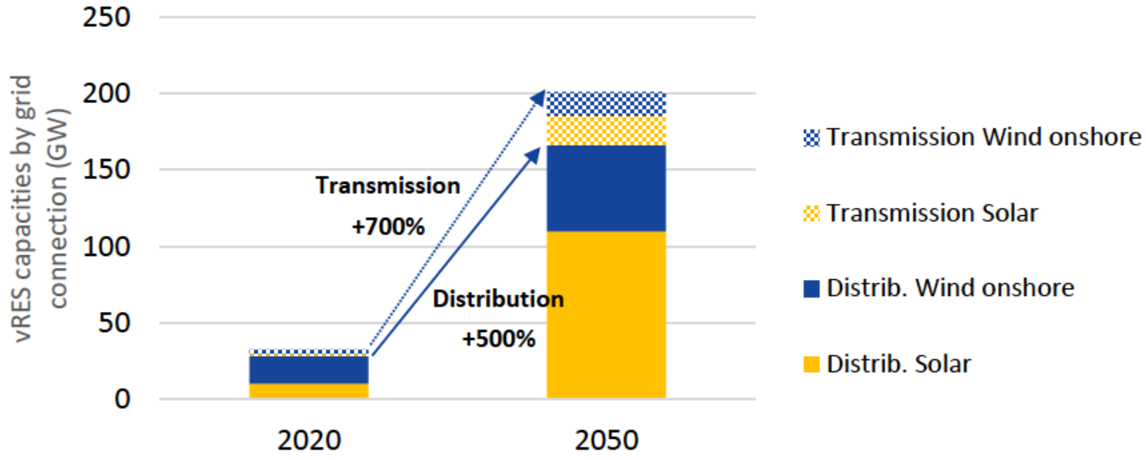

Figure 32 - Projected wind and solar capacities connected to the distribution and transmission grid in France in the M23 scenario of the RTE study. Source: own illustration based on (RTE, 2022).

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[29] For the sake of comparison, current natural gas storage capacities in Germany equal 245 TWh.

In parallel, the **enhanced electrification of energy consumption** (notably from electric vehicles and heat pumps) **puts additional pressure on distribution networks**. The RTE study for France forecasts an increase of the demand connected to the distribution grid of over 15% (RTE, 2022). And the Agora Climate Neutral 2045 study for Germany forecasts a more than 50% increase of the demand connected to the distribution grid, cf. Figure 33 (Stiftung Klimaneutralität, Agora Energiewende, Agora Verkehrswende, 2021).

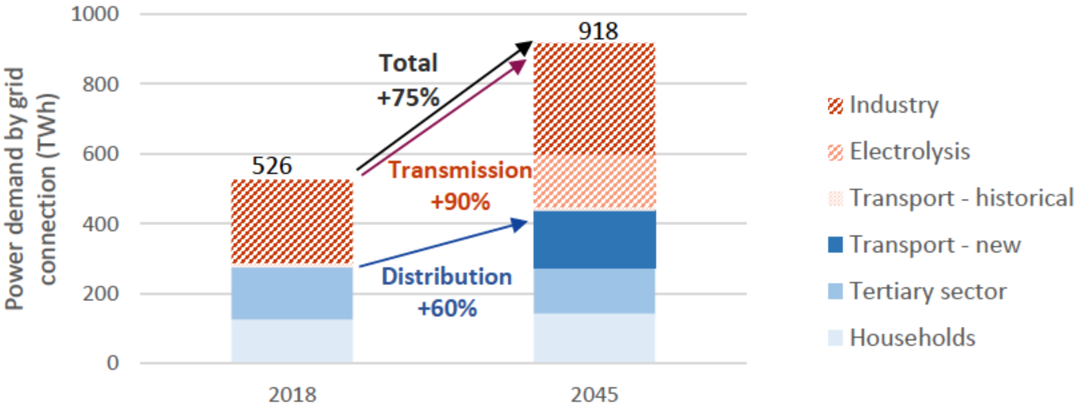

Figure 33 - Evolution of power demand depending on the type of grid connection in Germany (in GW). Source: own illustration based on (Stiftung Klimaneutralität, Agora Energiewende, Agora Verkehrswende, 2021).

This load growth mostly affects primarily distribution grids in urban areas, while the increase of renewable production mainly occurs in rural areas. The simultaneous increase in production and load does not necessarily imply a levelling out between production and consumption due to a **temporal and geographical incoherence**. In addition, fast-charging facilities increase the pressure on distribution grids, and a temporal offset remains between usual electric vehicle charging and decentralized solar generation patterns: electric vehicles are usually charged in evening hours and overnight, while solar plants produce during midday hours.

The **need to reinforce the distribution grids results in a considerable increase of annual grid costs**, which may, in worst cases, double compared to current numbers by 2050 and put an additional burden on final consumers. These annual distribution grid costs are the highest for direct electrification and RES-intensive scenarios. In the BMWi study, the cost increase is highest for the TN-Strom scenario, which is the scenario featuring highest direct electrification levels, rising from 7.5 Bn€ in 2018, to 10 Bn€ by 2030 and more than 15 Bn€ by 2050 (BMWi, 2021). In the RTE study (RTE, 2022), the highest costs are for the scenarios with the highest deployment of renewable capacities (M0 and M1 scenarios), implying costs to evolve from about 3 Bn€ today to more than 5 Bn€ by 2050.

4.3.3 Only reinforced transmission can connect new electricity production and conversion sites and cope with rising transit power flows

Transmission grid capacities are expected to increase due to various drivers. First, there is the volume dimension: power demand and power flows are expected to grow. Wind and solar power generation are likewise expected to increase, further requiring higher connection capacities compared to traditional power supply technologies due to lower load factors.

In addition, the **installation of large renewable plants, notably offshore windfarms, requires an altered grid topology** as future production sites will differ from conventional power plant sites, implying grid extensions.

The **increase in trans-European transit power flows** put more pressure on the national transmission grids. French TSO RTE estimates pure transit flows to double by 2040 and to triple (or more) by 2050 (RTE, 2022). National transmission grids are notably expected to facilitate transfers of wind power from north to south and solar power from south to north, with seasonal, weekly and daily fluctuations, cf. Figure 34.

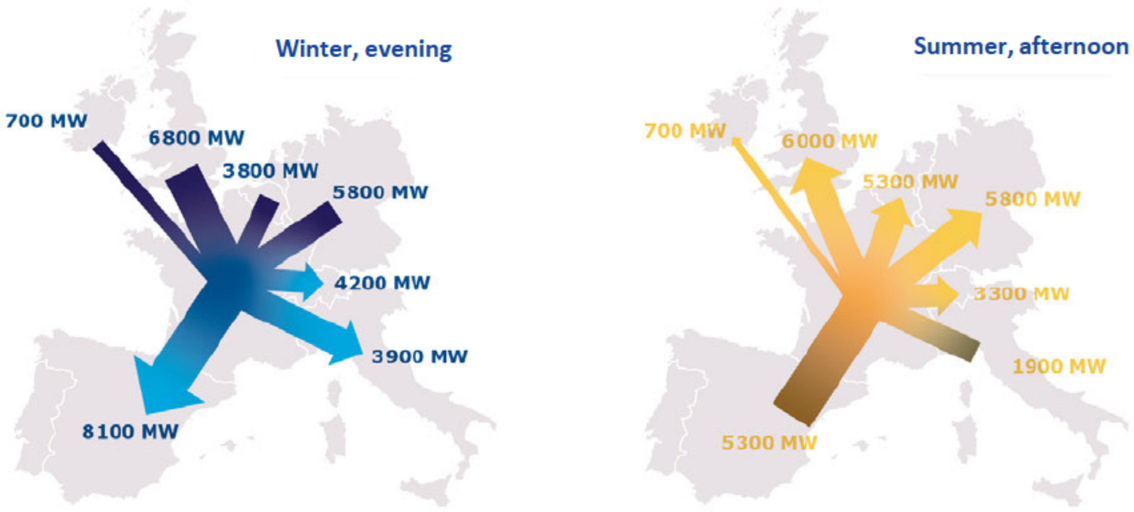

Figure 34 - Projected trans-European power flows transiting through the French transmission grid in 2050. Source: (RTE, 2022).

Finally, **the European transmission grid is ageing** and has to be renewed and maintained to ensure an appropriate quality of service. The need for infrastructure renewal has to be anticipated so that an excessive proportion of installations does not need to be replaced at the same time. Renewal expenditures for the French transport grid from the RTE study are depicted in Figure 35. Uncertainties remain regarding the required investments (around 20% uncertainty in France according to RTE).

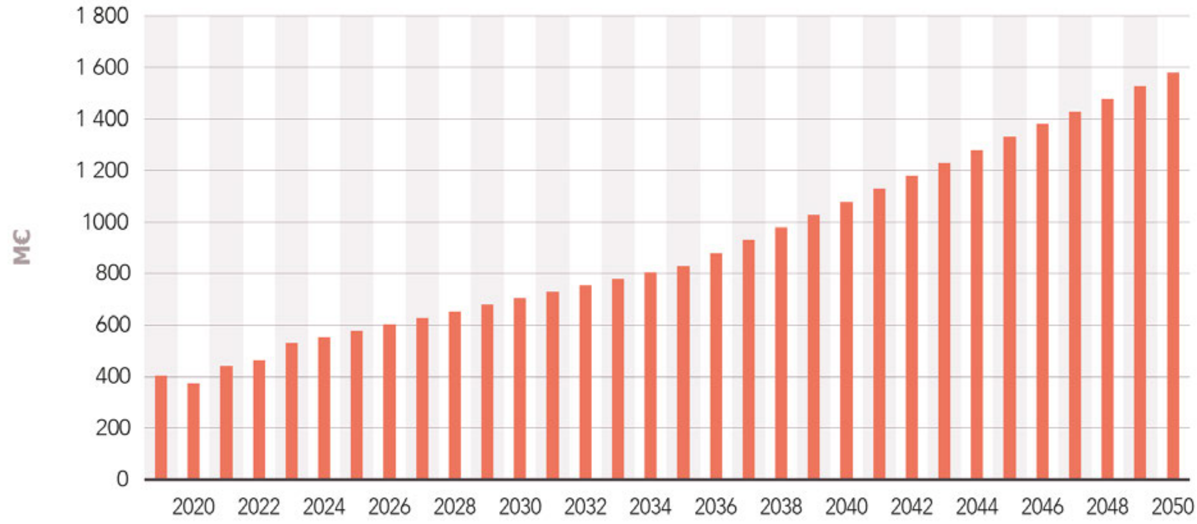

Figure 35 - Projected renewal expenditures for the French transport grid (M€). Source: (RTE, 2022).

Available figures for France and Germany foresee grid reinforcements of 2-14% in the installed length (in grid km) of the transmission network by 2030 compared to the length in 2020 and 9-57% by 2050[30].

4.3.4 Cross-border exchange capacities and flows increase to facilitate regional cooperation.

All scenarios come to the conclusion that **cross-border power exchange will increase**, assuming that the expansion of cross-border exchange capacities will equally go along. By 2050, import capacities are expected to increase by at least 70% (e.g., in the case of Germany or Switzerland, cf. Figure 36) and may more than triple (e.g., for Belgium and France).

Cross-border power exchanges will facilitate an efficient utilisation of the most favourable wind and solar sites, facilitate RES integration and enable regional cooperation on flexibility provision.

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[30] The figures are based on the BMWi study over the 3 scenarios for Germany for the transmission grid (BMWi, 2021), and on the RTE Study over all scenarios for grid deployment within French regions (RTE, 2022). The length of the German transmission grid will rise from 36 000 km in 2020 to around 41 000 km by 2030 and 50 000 to 55 000 km by 2050. French regional transmission grids (excluding 30 000 km of very high voltage lines, featuring 400 kV and partially 225 kV voltage levels) rise from 70 000 km in 2020 to around 75 000 km by 2030 and 77 000 to nearly 100 000 km by 2050, depending on the scenario.

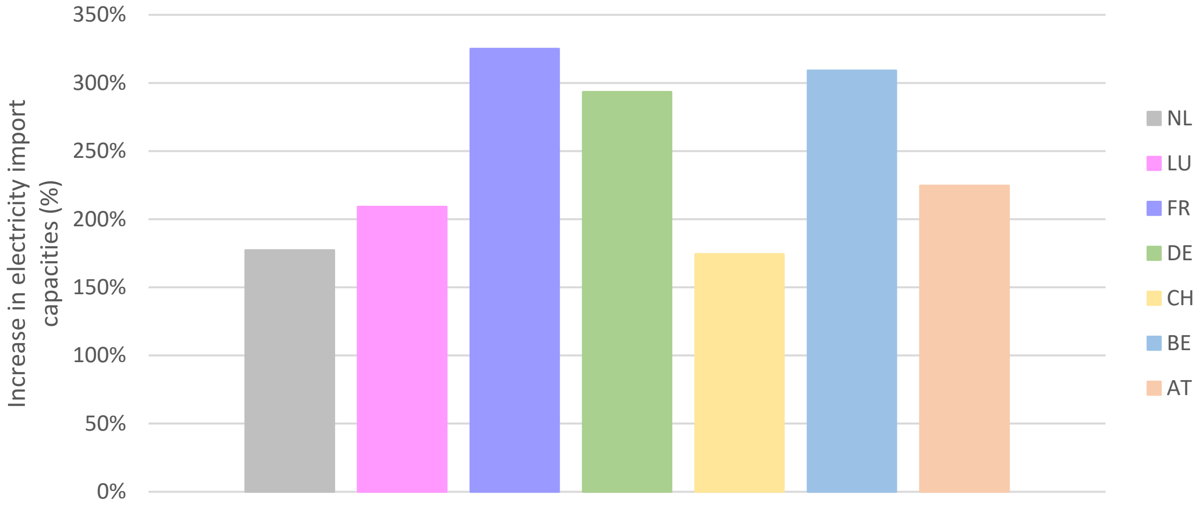

Figure 36 – Increase in electricity import capacities (NTC) by 2050 compared to 2020[31]. Source: Own illustration

It is important to note that the expansion of cross-border exchange capacities needs to be aligned with the expansion of internal transmission grids in order to facilitate transit flows across the entire Penta region and even beyond (cf. Section 4.3.3).

4.3.5 Integrated infrastructure planning as prerequisite of a cost-efficient and timely transition

As required by Penta, a distinct focus was set on infrastructure planning procedures across Penta member countries, even though most of the scenario assessments analysed do not focus on network planning. Instead, network development plans (NDPs) of the different Penta countries[32] were analysed and compared, complemented by the 2021 ACER Opinion on the Electricity National Development Plans (ACER, 2021), cf. Table 2. The comparison reveals that the publication of electricity NDPs differs in terms of time and frequency across Penta countries, with most NDPs being published every two years, as recommended by ACER. ACER finds that study horizons up to the year n+15 were used in most of the NDPs. But given the strong expansion needs in the next decades and the long time horizons

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[31] The following scenarios were compared: CLI from the PSI study for Switzerland (Paul Scherrer Institute, 2021), TN-H2 from the BMWi study for Germany (BMWi, 2021), RTE study for France (RTE, 2022), Elia study for Belgium (Elia Group, 2021), Netbeheer study for the Netherlands (Netbeheer, 2021), NECP scenario for Luxembourg (Luxembourg Ministry of the Environment, Climate and Sustainable Development, and Luxembourg Ministry of Energy and Spatial Planning, 2018), and TYNDP 2022 for Austria (ENTSO-E, ENTSOG, 2022). Long term values for Luxembourg and Austria are 2040 projections resp. from the Luxembourg's NECP and the TYNDP 2022.

[32] In the case of Austria, two TSOs issue their own separate NDPs whereas in the 4 German TSOs prepare a single and joint NDP.

for planning and construction, longer time horizons may be more appropriate.[33] In most countries, there is only limited cooperation between DSOs and TSOs (e.g., in terms of harmonisation of input data). However, several (yet not all) NDPs apply the same policy objectives as outlined in the National Energy and Climate Plans (NECPs) and align partially with the assumptions or outputs from ENTSO-E's Ten-Year Network Development Plan (TYNDP).

Table 2 - Comparison of electricity network development plans in Penta countries. Source: own design incorporating information from (ACER, 2021).

TSO NDPs	AT	BE	CH	DE	FR	LU	NL
Publication frequency	1 year	4 years	4 years	2 years	2 years	2 years	2 years
All territory covered by DSO NDPs	No	Yes	No	No (subject to change)	No	Yes	Yes
Input alignment of DSO/TSO NDPs	N/A	Yes	Yes	Yes	No	No	No
Consultation and joint activities of DSOs/TSOs	N/A	No	Yes	Yes	Yes	Yes	Yes
NDP alignment with NECP	No info	No info	No info	Common objectives: carbon budget, RES goals, EV fleet…	Common objectives with the national strategy on which the NECP is based	NDP built to align with NECP	NDP 2020 based on the Dutch Climate Agreement, on which the NECP is based.
NDP-TYNDP consistency	Inputs, Outputs	Inputs, outputs, CBA methodology, modelling	Outputs	Inputs	Outputs, CBA methodology, Modelling	Inputs, outputs	Inputs

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[33] E.g., the time horizon of the NDP in France increased from 10 to 15 years. Germany intends to extend the planning horizon to 20 years in its upcoming NDP.

In none of the countries, the electricity NDP is prepared jointly in order to develop multiple energy sectors (e.g. electricity-gas). However, there is scientific evidence that a joint modelling approach for power and gas infrastructures may identify synergies between the two systems and ultimately lead to lower investments needs and a more efficient utilisation of existing infrastructure, cf. Figure 37.

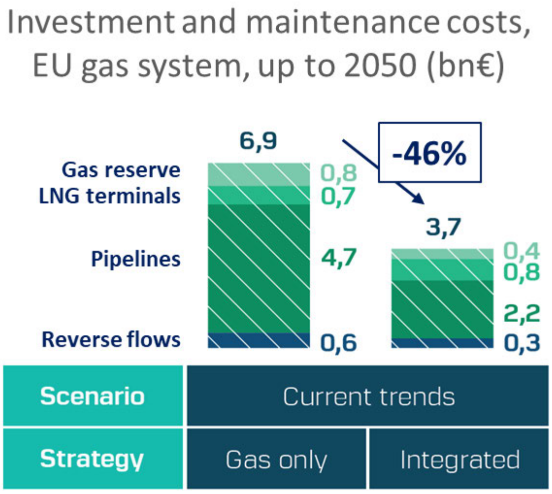

Figure 37 - Change in CAPEX and operational costs for the EU gas system up to 2050 between a pure gas-based approach and a joint power-gas approach. Source: (Artelys, 2016).

The ADEME report for France (ADEME, 2021) illustrates that a **joint optimisation of grid investments and RES siting (plus potentially electrolyser siting) may lead to lower overall costs**. That is, RES capacities should not per se be installed at sites featuring highest capacity factors, but the economic decision should also integrate the costs related to connect additional RES capacities and how to integrate them most cost-effectively.[34]

4.4 Methodologies underlying the scenario assessments

A closer look at the modelling approaches underlying the different scenario assessments reveals that for most countries recent model-based techno-economic assessments of transition pathways are available. Yet, a multitude of models are applied, cf. Table 3, but only two models were applied for two different studies (among those short-listed for the present analysis), namely RTE's Antares and Prognos' Energy Systems Model. The model owner often differs from the entity authoring or publishing the actual scenario assessment. The extent of publicly available data accompanying the scenario assessments is quite heterogenous across the sample of analysed studies, yet, in most cases access to quantitative information (in particular at hourly granularity) is very restricted.

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[34] This holds true for countries where RES potentials significant exceed the actual need for installation. In countries where the full RES potentials need to be exploited, such constraints are of temporal validity.

Table 3 - Overview of models applied for the scenario assessments

Country	Study	Author	Model owner	Model name
AT	NECP	BNT	-	-
AT	(Bundesministerium Nachhaltigkeit und Tourismus, 2019)	BNT	-	-
BE, DE	(Elia Group, 2021)	Elia	RTE	Antares
BE	(DG Environment, 2021)	DG Environment	-	-
CH	(Bundesamt für Energie BFE, 2021)	SFOE	Prognos	Energy Systems Model
CH	(Paul Scherrer Institute, 2021)	Paul Scherrer Institute	Paul Scherrer Institute	Swiss TIMES Energy Model
DE	(BMWi, 2021)	BMWi	Fraunhofer ISI	Enertile 7
DE	(Stiftung Klimaneutralität, Agora Energiewende, Agora Verkehrswende, 2021)	Agora	Prognos	Energy Systems Model
DE	(Agora Energiewende, 2022)	Agora	Prognos	Energy Systems Model
FR	(ADEME, 2021)	Ademe	Artelys	Artelys Crystal Super Grid
FR	(RTE, 2022)	RTE	RTE	Antares
LU	(Luxembourg Ministry of the Environment, Climate and Sustainable Development, 2021)	MECDD	-	-
LU	(Luxembourg Ministry of the Environment, Climate and Sustainable Development, and Luxembourg Ministry of Energy and Spatial Planning, 2018)	Luxembourg Ministry of the Environment, Climate and Sustainable Development, and Luxembourg Ministry of Energy and Spatial Planning	-	-
LU	(Creos, 2020)	CREOS	-	-
NL	(Netbeheer, 2021)	Netbeheer	Quintel	Energy Transition Model
EU	(ENTSO-E, ENTSOG, 2022)	ENTSO-E	Energy Exemplar	Plexos
EU	(European Commission, 2018)	European Commission	E3-Modelling	PRIMES

When it comes to the **modelling scope**, we observe likewise a relevant heterogeneity (cf. Table 4), which can be primarily explained by the fact that the different studies were prepared for different purposes (long-term strategies, network development plans, policy analyses). While some models focus exclusively on the power sector and consider sector coupling and interlinkages with other energy carriers (e.g. hydrogen) only via exogenous assumptions, others extend the scope to the entire energy sector (partial equilibrium models), and apply a fully integrated approach when it comes to multi-energy modelling and sector coupling. In some models, the analysis is restricted to a pure dispatch optimisation (testing how exogenously given power generation capacities may meet power demand), whereas more complex models allow to dimension the entire parc of capacities through a dedicated capacity optimisation. In terms of assets covered in the models, the least complex models consider power generation and storage only, whereas more complex models also consider energy system infrastructure (e.g. cross-border capacities) or internal electricity grids. It is common to all models to apply a cost-minimisation approach in order to reflect perfect (electricity) market functioning.

The level of complexity applied typically depends on the purpose of the analysis.

Table 4 - Overview of modelling scopes

	Low complexity	Medium complexity	High complexity
Energy system coverage	**Power** sector (RTE)	**Energy sector** models or model clusters (partial equilibrium model) (SFOE)	
Sector-coupling/multi-energy modelling	Focus on hydrogen-related power demand: **exogenous electrolysis demand**, endogenous optimisation of electrolyser capacity and operation (RTE)	**Soft link** between demand model and energy model to link energy carriers with end-uses energy demand with focus on power technologies (especially P2X) (BMWi)	PLUS Consideration of **non-power technologies** (SMR, heat boilers, etc.) (PSI with SMR and ATR) and explicit representation of **alternative energy carriers** (gas, hydrogen) (PSI)
Objective function	**Cost minimization**		
Decision variables	**Production dispatch** (installed capacities as exogenous input) (Quintel)	PLUS **Capacity expansion** optimisation (e.g., generation, transmission, storage) (ENTSO-E, RTE)	
Infrastructure scope	Electricity **cross-border** transmission, storage (EC)	PLUS **Subnational electricity grid** expansion (especially for RES integration) (Ademe)	AND/OR **Energy system infrastructures** (electricity, hydrogen, gas, CO2 and possibly heat systems) (Quintel)

5 Convictions and link to the underlying observations

This section introduces twelve convictions which were derived from the observations listed in the previous section. Each conviction is shortly described (incl. a reference to the underpinning observations), followed by an indication of remaining uncertainties (in italic).

A non-exhaustive list of indicative actions that illustrate how to put the convictions into action is available in the Annex of this report, cf. Section 7. Table 5 in Section 7.1 indicates the relationship between all observations, convictions and actions.

5.1 Power sector decarbonisation by 2035

The **power sector needs to be decarbonized as early as possible, ideally by 2035**. Across the national studies analysed the power sector will be predominantly or fully decarbonised by 2035, with carbon intensities below 50 g/kWh (see Observation 4.2.1). Low carbon technologies are available to achieve this target. The decarbonisation of numerous hard-to-abate sectors (such as industry, transport, buildings) depends on power sector decarbonisation (via direct electrification, i.e. the direct use of electricity, and indirect electrification, that is converting electricity into hydrogen and other synthetic derivatives). This implies a large expansion of the power sector. The increase in domestic power demand (which doubles in some Penta countries by 2050) is illustrated in Observation 4.1.1.

The IEA confirmed that 2035 is a relevant key date for the decarbonisation of the power sector, in order to ensure an economy wide decarbonisation by 2050, cf. Figure 38.[35]

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[35] This objective was also endorsed by the G7 at their summer summit 2022.

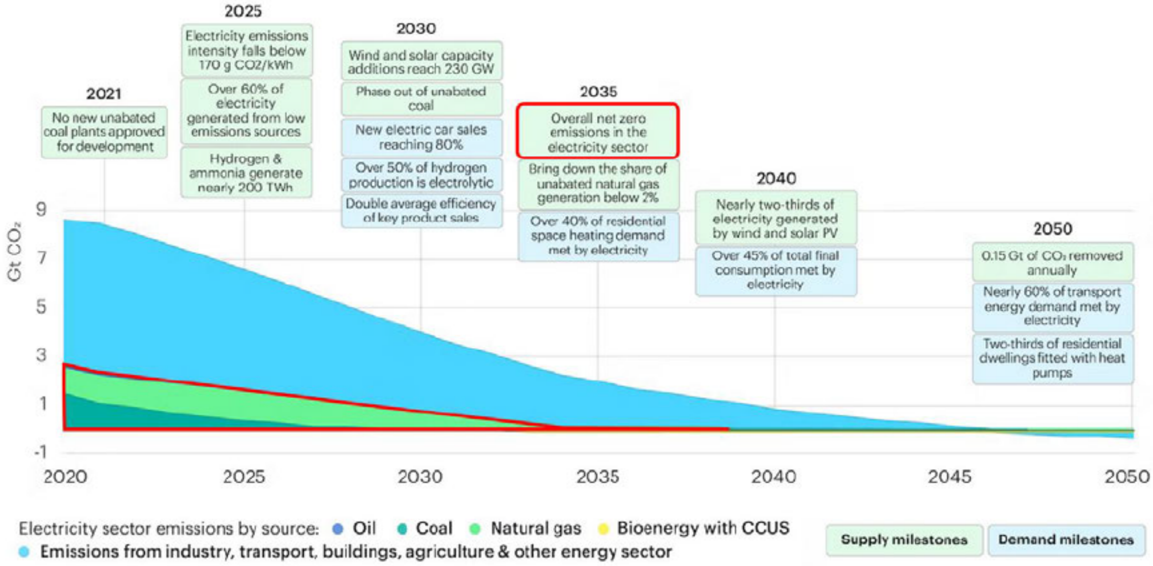

Figure 38 - G7 energy-related emissions and electricity sector milestones in the Net Zero Emissions by 2050 Scenario. Source: (IEA, 2021).

> ***Uncertainties*** *remain whether a decarbonisation of the power sector is sufficient or whether there is actually a need for negative emissions from power generation through biomass-firing in combination with carbon capture and storage (BECCS), which might be required in the long run to compensate for non-removable emissions in industry (process emissions) and agriculture.*

5.2 Renewables are the main pillar of decarbonisation

For the decarbonisation of the power supply side, renewables are the main pillar. Domestic solar PV and wind power production in the Penta region (including in the North Seas) will play a vital role for achieving the decarbonisation targets. The sum of solar and wind capacities across the most ambitious scenarios mounts up to 1100 GW by 2050 vs 180 GW today (that is a factor of 6, cf. Observation 4.2.2,). Yet, the roll out of renewable installations needs to strongly speed up: annual solar PV installations need to double in the current decade compared to the previous one and they need to double again after 2030.[36] Faster permitting procedures, among other measures, will help to unlock these investments.

In the long-run, in addition, **important amounts of renewable electricity are foreseen to be imported** notably from the Baltic Sea, Southern Europe, and possibly the MENA region, requiring additional

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[36] See also the Joint Statement on the North Seas Energy Cooperation (NSEC) from 12/09/2022, wherein NSEC members recognise their historic opportunity to accelerate the delivery of regional offshore renewable energy.

cross-border capacities. In many scenarios, electricity imports cover between 10% and 30%, and going up to 50% in selected scenarios, of total power demand by 2050. Additional internal and cross-border capacities are needed to enable such import volumes from other European countries (see Observations 4.3.3 and 4.3.4, but also Conviction 5.7).

The need for and role of other more immature low carbon power generation technologies (e.g., small modular reactors, tidal and wave power production and ultra-deep geothermal, nuclear fusion), remains ***uncertain****.*

Uncertainty *also remains regarding the import ratio between electricity and decarbonised molecules, as well as the source countries outside Penta and potentially over-seas exporting the hydrogen (or hydrogen derivatives), see Observation 4.1.3.*

5.3 "Energy efficiency first" releases pressure from the power system

The **demand side decarbonisation** needs to rely on three strategies, which are to be addressed in the following order of priority: **energy efficiency first**[37]**, direct electrification second, green/decarbonised molecules third** (i.e., the use of synthetic energy carriers but also sustainable biogas/biomethane/bioliquids).[38]

Energy efficiency enables to lower the expected increase in power demand, thus minimising the need for infrastructure investments (e.g., French TSO RTE projects power demand to increase only by 24% between today and 2050 instead of 62% in case efficiency measures are widely activated). Building renovation (whose rate is expected to double to more than 2%/year in different scenarios, cf. Observation 4.1.4) further facilitates the roll-out of CAPEX-intensive heat pumps as they may operate more efficiently and require lower installed capacities.

Secondly, energy efficiency lowers energy demand and hence **reduces the need for imports** (on which most Penta countries will still heavily rely in the long-run, in particular for electricity, hydrogen and hydrogen derivatives) and ultimately increase energy sovereignty (cf. Observation 4.1.1).

However, the magnitude of accelerating building renovations is subject to ***uncertainty****, for example due to a lack of skilled labour and the persisting owner-tenant dilemma. The feasibility and*

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[37] The "Energy Efficiency First" principle is also support by the European Commission, cf. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-first-principle_en

[38] It must be noted that energy efficiency, direct and indirect electrification are all required. Insufficient progress on any of these pillars would mean an increase to fail on meeting the decarbonization objectives, or to meet them at much higher cost.

effectiveness of a circular and more energy efficient economy is also questionable, notably due to the risk of a rebound effect following energy efficiency improvements.

5.4 Direct electrification comes with immediate benefits

Apart from energy efficiency, shifting from fossil energy carriers to the **direct use of electrification is key to decarbonise the demand side.** The direct use of electricity is the preferred solution over green molecules if technically feasible and cost-competitive, in particular in passenger road transport (full electric vehicles), as well as for low/medium temperature heat supply in buildings and industry (through heat pumps), cf. Observation 4.1.2. Yet, this implies a significant increase in electricity demand (by up to 40% in 2030 and which may more than double until 2050, compared to today's levels, cf. Observation 4.1.1).

Direct electrification is not only **more efficient than indirect electrification**, as it requires less electricity to provide the same energy service. **Direct electrification also comes with immediate benefits** in terms of emission reduction. For instance, with the current power mix, electric vehicles outcompete the carbon footprint of conventional cars even in countries with a high carbon intensity of power generation. The same applies for heat pumps in buildings and for low and medium industrial heat.

*In specific sectors, **uncertainty** remains about the respective potential role of direct electrification and hydrogen, notably regarding short/medium-haul aviation, heavy road transport or high temperature industrial heat. In addition, hybrid heat pumps[39] might play a transitional role, but would require gas infrastructure to be maintained at very low gas demand volumes, which implies significant costs on the one hand and may hinder or delay, on the other hand, a cost-optimal repurposing of this infrastructure towards transporting hydrogen.*

5.5 Decarbonised molecules will play a limited but crucial role

If energy efficiency and direct electrification are insufficient for an effective (or cost-efficient) decarbonisation of specific demand sectors, renewable and low-carbon molecules (hydrogen and its derivatives as well as sustainable biomethane and bioliquids) will play a limited but important role. The use of **hydrogen and its derivatives should be focused first on hard-to-abate sectors**, which mainly

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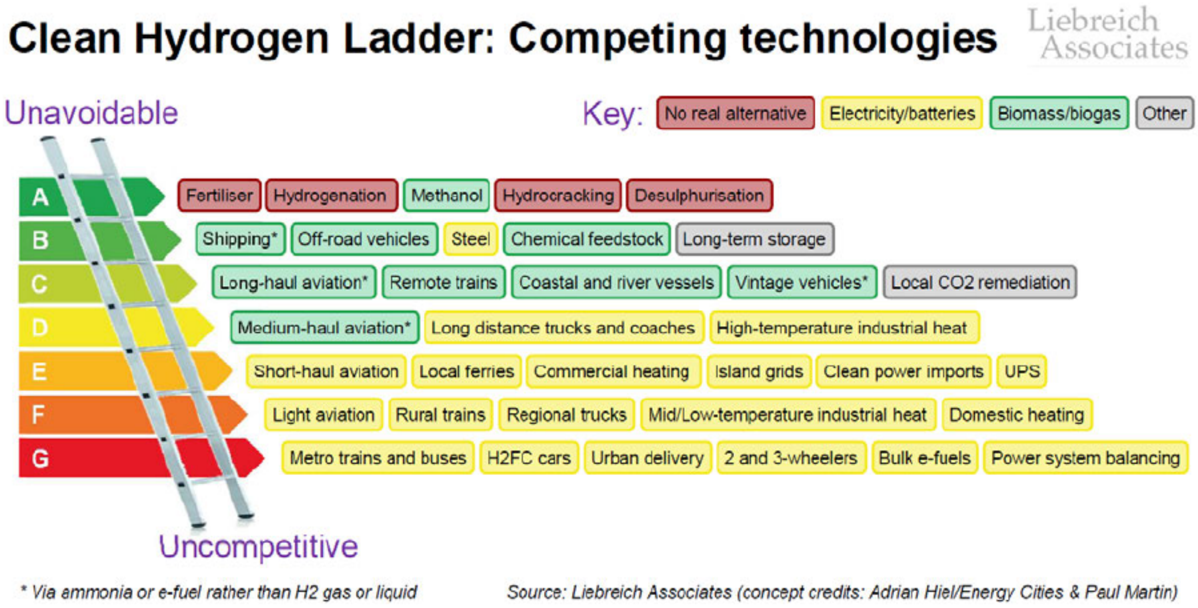
[39] Hybrid heat pumps mainly use electricity, but can work on gas during the coldest moments of the year or when power systems are under stress.

are feedstocks, steel, deep-sea shipping and long-distance aviation (cf. Figure 39). The magnitude of indirect electrification is illustrated in Observation 4.1.3. Its participation to the total power demand is detailed in Observation 4.1.1.



* Via ammonia or e-fuel rather than H2 gas or liquid

Source: Liebreich Associates (concept credits: Adrian Hiel/Energy Cities & Paul Martin)

Figure 39 - Clean hydrogen ladder: competing technologies. Source: (Liebreich Associates, 2022).

In the short term, the use of **green hydrogen should be largely prioritized for industry**, currently the main consumer of grey hydrogen, rather than for meeting new hydrogen demands.

In the long term, some ***uncertainty*** *remains on the role that hydrogen has to play in some sectors compared to direct electrification (cf. Conviction 5.4). In addition, the extent of low-carbon gas' participation in the power sector is still discussed, notably regarding the role of biomethane and hydrogen in peak power generation (cf. Observation 4.2.1), and the need for hydrogen or its derivatives as seasonal power storage (cf. Observation 4.3.1).*

5.6 Hydrogen economy needs to be established now

As detailed in Conviction 5.5, hydrogen will play a limited but important role to achieve the economy-wide decarbonisation. To enable the trade and use of hydrogen and of its derivatives, the way towards a European hydrogen economy needs to be paved now. Thus, **establishing networks, developing a market and framing regulations** should be started now. By 2030, rather regional hydrogen networks and clusters appear, being partially interconnected. By 2050, a more complete network – and significant amounts of H2 imports (in particular in DE, BE, NL, and LU with imports making up for 50%

of domestic demand – or more[40]) make a European hydrogen network indispensable, cf. Observations 4.1.3, 4.2.4. **Penta is expected to play a central role in this framing**, due to its geographical location at the heart of Europe, to its existing hydrogen demand, to its high renewable potentials, and to the existing gas infrastructure (which could be repurposed at a later stage to hydrogen).

Regarding the import of hydrogen, it remains ***uncertain*** *where renewable and electrolyser capacities will be located and which share of cross-border exchanges (imports and exports) will be in the form of power or hydrogen. This requires a more coordinated assessment (cf. Conviction 5.8 and Observation 4.3.5.). In addition, the form (hydrogen or a derivative) and the origin of hydrogen imports (from Europe and abroad) is still uncertain. Finally, it is still open whether there is a need for a hydrogen distribution grid, or whether hydrogen will mainly be transported to major centralised consumers via a transmission network.*

5.7 Power grid capacities need to increase substantially

Internal electricity transmission and distribution networks face unprecedented challenges, most notably a significant rise in connected renewable capacities and demand volumes, cf. Observations 4.3.2 and 4.3.3. In some scenarios, RES capacities connected to distribution grids increase by a factor of 5 to 7 compared to current levels,[41] demand volumes by a factor of 2 (with peak loads potentially featuring an even more important rise in case of suboptimal load profiles, cf. also Conviction 5.10). In combination with decreasing system inertia, grid aging, and rising transit flows, this results in a strong need to increase power grid capacities, through a smarter and more efficient operation of existing assets (e.g., via dynamic line rating, phase-shift transformers, power electronics), and through grid reinforcement. Annual distribution grid costs are expected to increase by 25% to 100% until 2050, annual costs for transmission grids may rise even more importantly by up to a factor of 4.

The extent to which operational optimisation of existing infrastructure can ultimately reduce the need for grid reinforcements remains ***uncertain****, as grid technologies continuously evolve.*

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[40] The renewable power generation potential of the Penta countries (combined) would theoretically be sufficient to meet future hydrogen demand, yet 1) this would nonetheless require reinforced cross-border interconnection capacities for electricity or hydrogen between Penta countries and 2) it is uncertain whether there is sufficient acceptance for a significant increase in renewable power generation capacities (in particular for on-shore wind in France).

[41] In the case of France, 80% of all future vRES capacities are expected to be connected to distribution grids (RTE, 2022).

5.8 A coordinated approach to energy system planning

In addition to the previous conviction, it is important to note where and how much (cross -border and internal transmission) power line capacity needs to be added. But actually, this depends on a lot of factors, such as the siting and capacities of new renewable capacities, electrolysers, electricity but also hydrogen and gas storage potentials, new and existing gas and hydrogen pipelines, load centres, etc. **Identifying the optimal system configuration of the future energy system and the pathway to get there is probably the challenge of the coming decades.** This challenge can only be mastered in a coordinated and integrated manner.

Two fields of application seem particularly apt for enhanced coordination and integration: 1) Countries within Penta and beyond should **coordinate when fixing national strategies and objectives** (e.g., on the electrolyser deployment), taking into account the visions and scenario assumptions of neighbouring countries; 2) The **planning of network development should be more integrated** (cf. Observation 4.3.5), ideally including all grid-bound energy carriers (electricity, gas, hydrogen), as they are interdependent, covering the national and regional level, including the vision of all connected stakeholders, and aligning with decarbonation strategies.

This will be a step forward to **identify the optimal trade-off between** the exploitation of high-performance RES potentials, electrolyser siting, and optimised power/gas/hydrogen grid adaptation (management, repurposing, reinforcement). It requires a significant effort of coordination (i.e., transaction costs), but allows for cost-efficient infrastructure deployment and avoids stranded assets. A coordinated approach is beneficial as it drives down overall system costs and thus the financial burden on consumers and tax payers. The importance of cooperation regarding cross-border exchanges, energy storage, and power supply is respectively detailed in Observations 4.3.4, 4.3.1 and 4.2.4.

These coordinated strategies have to deal with various ***uncertainties****, most notably regarding the deployment of a pan-European hydrogen network (that will depend on the renewable and electrolyser's siting, and on the trade-off between power lines and hydrogen pipelines), on the scale and effective feasibility of gas pipeline repurposing, and on the magnitude, origin and form of hydrogen imports.*

5.9 Flexibility - a key element of the energy transition

Flexibility needs will significantly increase both on short and long timescales, cf. Observation 4.2.3. Daily flexibility needs are expected to rise by a factor of three to four at the Penta-level, and more than a factor of five in selected Penta member countries until 2050. Seasonal flexibility needs face a less pronounced but nonetheless very important increase (as solar and wind generation feature seasonal patterns, and heating is further electrified). **Regional cooperation and enhanced cross-border interconnection may soften the increase.** By "simply" interconnecting the Penta market area (copper plate), demand and RES variation flattens out significantly, implying a 10% reduction in flexibility needs (Trinomics, Artelys, 2023). That is, regional cooperation lowers costs and facilitates RES system integration.

Flexibility needs will be met by various centralised and decentralised technologies, including supply, storage, network infrastructure and demand-side assets. It is key that all these assets may effectively contribute to flexibility supply (cf. Conviction 5.12).

*Some **uncertainty** remains on the magnitude of participation of renewable or low-carbon gas in the power sector, notably regarding the role of biomethane and hydrogen in peak power generation, and the need for hydrogen or its derivatives as seasonal power storage.*

5.10 Additional power demand can and must be flexible

One source of flexibility, currently still remaining largely untapped (even though the current energy crisis has proven that price signals can effectively alter consumption patterns) is demand side flexibility (DSF). **New electricity consumers** (such as electric vehicles, heat pumps or electrolysers) **feature a high potential of demand side flexibility**[42], cf. Observations 4.1.2 and 4.1.5. **Yet, DSF should not be considered as a nice-to-have feature, but a must-do.** Otherwise, peak demand will excessively increase, implying an oversizing of the power supply fleet and electricity grids.

*The potential participation of specific technologies to demand side flexibility is still subject to **uncertainty**: the extent to which trucks will be electrified and will contribute to demand flexibility, and the flexible operation mode of electrolysers, which counteracts the objective of maximal full load hours.*

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[42] This flexibility is notably enabled through the fact that these consumers typically explicit or implicit storage capacities at their disposal, i.e. batteries in the case of EVs, heat storage or the thermal inertia of buildings for heat pumps and hydrogen storage for electrolysers.

5.11 Energy storage facilitates RES integration

Energy storage for power, heat, hydrogen as another source of flexibility is a **key enabler of renewable integration and is essential for the continuous equilibrium between demand and supply,** cf. Observation 4.3.1. The storage of electricity with batteries and pumped hydro storage allows to integrate wind and solar power production by balancing notably hourly, daily and weekly variations and matching with variable demand. Gas and hydrogen storage capacities are indispensable in particular for seasonal balancing. Gas storage allows for peak power production and hydrogen storage enables a flexible operation of electrolysers, thus harvesting their flexibility potential.

However, **storage capacities are not evenly distributed across all Penta countries**. Salt caverns for hydrogen storage are situated rather towards Northern Germany and the North Sea basin, pumped hydro potentials are in particular located in the Alps. Thus, a regional cooperation is crucial to facilitate the efficient use of storage potentials and make them available to all countries.

> ***Uncertainty** remains regarding the competition between vehicle-to-grid and batteries, as well as regarding the suitability and cost-efficiency of specific geologic hydrogen storage types.*

5.12 The transition requires a future-proof market design

All the developments mentioned in the **precedent convictions require a future-proof electricity market design** to integrate the beforementioned technologies in the system (that is, setting the right investment incentives and a cost-efficient operation) and to ensure resource and transmission adequacy. Specific **fields of action** can be addressed:

- market areas should to be further interlinked (in terms of reinforced cross-border interconnection capacities but also via market integration, cross-border cooperation to share reserve capacity and net balancing, the joint development of offshore wind energy parks, so-called hybrid projects),
- sufficient investment incentives should be provided (e.g., through capacity remuneration mechanisms),
- the participation of all flexibility sources should be enabled,
- and the potential reconfiguration of bidding zones could be investigated.

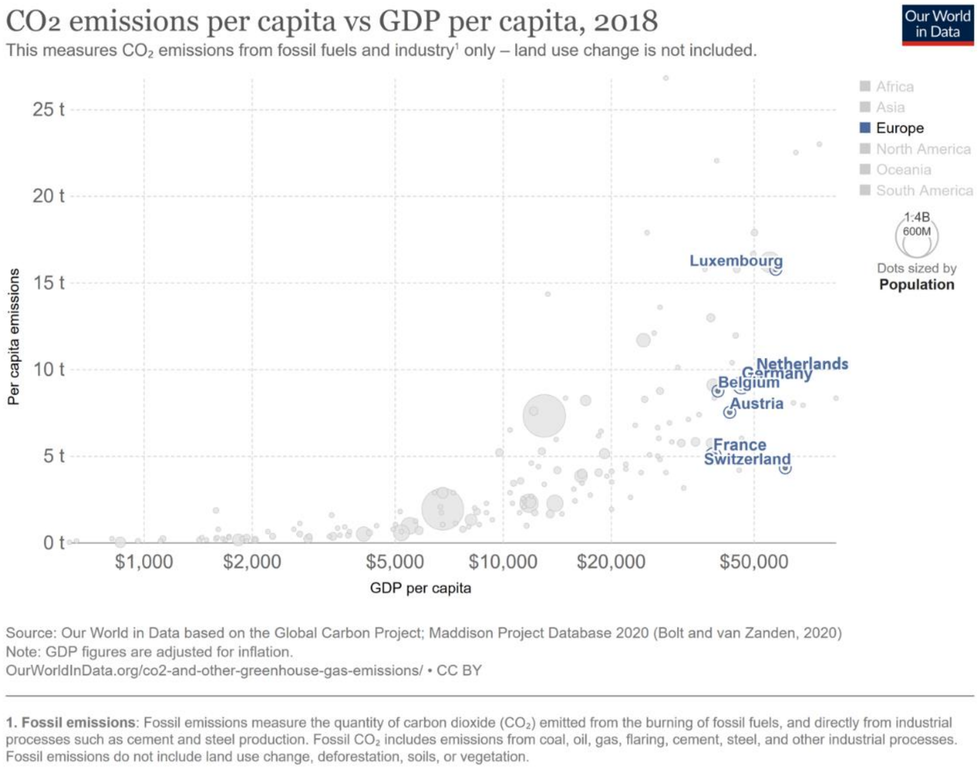
> *However, it is **uncertain** whether an appropriate market design that continuously facilitates the energy transition can be designed and implemented in a timely manner and whether all countries and market players are actually able to stay up-to-date with the developments. A full set of recommendations was developed in the parallel study prepared by* (Trinomics, Artelys, 2023).

6 Conclusions and recommendations

It is common to all scenarios analysed for the present study, that an **economy-wide decarbonisation requires a quick and full decarbonisation of the power sector**, ideally towards 2035. Mature and cost-competitive technologies are available to decarbonise power generation, and power may be used directly or indirectly (via the production of synthetic energy carriers, such as hydrogen or hydrogen derivatives) to decarbonise other, hard-to-abate sectors.

Also, most studies accord in the conclusion that achieving **power sector decarbonisation requires rapid action in various domains**: deployment of renewable and low-carbon power supply technologies, sector-coupling and the enhanced use of electricity in final energy demand (via direct and indirect electrification), enhanced flexibility supply to ensure power system stability, more efficient use and extension of power/energy system infrastructure (networks, storage), and an appropriate market design to trigger the required investments and allow for an efficient system operation. The convictions listed in Section 5 detail the different fields of required action in more detail.

Putting this into a larger context, the present assessment leads us to the conclusion that the countries of the **Pentalateral Energy Forum are particularly well placed to initiate or accelerate the required changes** for different reasons: the geographical location of Penta countries at the heart of Europe, the high RES potentials (wind on-shore, wind off-shore in the North Sea, hydro potentials in the Alps), the existing electricity and gas network infrastructure (with gas networks being subject to repurposing), a high level of industrialisation accompanied with a relevant existing level of hydrogen demand, the integration of most Penta countries in existing European market platforms. Making use of these favourable assets may make the Penta countries being the front-runners of the European energy transition, triggering reforms, launch technology roll-out (e.g. when it comes to a European hydrogen economy), speeding up ongoing transformation processes (for in terms of accelerated RES deployment) and being the critical mass to convince other European countries to go along. Ultimately, the Penta countries, counting among the wealthiest but also the most polluting countries of the world (cf. Figure 40), were responsible for only 4% of global emissions in 2017. However, they may showcase that a rapid and full power sector and economy-wide decarbonisation is achievable, while ensuring economic prosperity and a secure, affordable energy supply.


CO2 emissions per capita vs GDP per capita, 2018

This measures CO_2 emissions from fossil fuels and industry[1] only – land use change is not included.

Source: Our World in Data based on the Global Carbon Project; Maddison Project Database 2020 (Bolt and van Zanden, 2020)
Note: GDP figures are adjusted for inflation.
OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY

1. **Fossil emissions**: Fossil emissions measure the quantity of carbon dioxide (CO_2) emitted from the burning of fossil fuels, and directly from industrial processes such as cement and steel production. Fossil CO_2 includes emissions from coal, oil, gas, flaring, cement, steel, and other industrial processes. Fossil emissions do not include land use change, deforestation, soils, or vegetation.

Figure 40 - CO2 emissions per capita vs GDP per capita, 2018. Source: (Our world in data, 2023).

At the same time, the review of scenarios and technical reports also reveals that **diverse elements of transformation pathways are still subject to high uncertainty**. This includes:

- The potential need for **negative emissions** from the power sector to compensate for remaining emissions in other sectors (e.g. agriculture or unavoidable process emissions in industry);
- The long-term need and role for rather **immature low-carbon power generation technologies**, such as small modular nuclear reactors, tidal, wave, ultra-deep geothermal, nuclear fusion);
- The import ratio between green electricity and green molecules from outside Penta and outside the EU;
- The **feasibility and cost-effectiveness of direct electrification** in short/medium-haul aviation, heavy road transport, high temperature industrial heat, in comparison to the use hydrogen (derivatives) or sustainable biomass/biogas;
- The dimension and configuration of a **pan-European hydrogen network**, which depends on the geographical siting of future RES and electrolyser capacities and the trade-off between power lines and hydrogen pipelines;
- The magnitude, origin and form of **hydrogen imports** (e.g., gaseous vs liquid hydrogen, ammonia, methanol);
- The ability of (continuously) developing an **appropriate electricity market design** that facilitates the energy system transition but that simultaneously allows countries and market players to stay up-to-date with.

These topics of uncertainty merit to be further analysed via dedicated assessments, or more comprehensive R&D activities.

In addition, it is important to note the **limitations of the present study**. First, the various scenario assessments analysed for this study feature varying scopes (in terms of energy carriers/markets covered, geographical zones covered, technologies considered), apply different methodologies, and were prepared for purposes (strategic studies, network development plans, technology evaluations, market design studies). It is thus difficult to compare the results and condense these into very specific conclusions. Secondly, the assessments and technical reports analysed were published one to three years ago. They thus do not integrate the most recent evolutions, which were triggered by the Covid and the subsequent energy crisis, such as for instance most recent national announcements or the increased level of ambition incorporated in the RePowerEU program. The observations outlined in Section 4 may thus already be outdated. This also illustrates the limitations of a review of existing scenarios that aims to contribute to a vision building process which is expected to go beyond the current state-of-the-art.

It may prove efficient to f**ollow-up on the present study with a joint scenario building and energy system modelling exercise** on behalf of the Pentalateral Energy Forum, which is jointly coordinated by all Penta countries (cf. Conviction 5.8). Such a modelling exercise would ideally cover the entire EU, determine the transition pathways until 2050 (i.e., explicitly representing the years 2030 and 2040, at least), make use of an endogenous multi-energy capacity expansion and dispatch optimisation approach (i.e., integrating the power, methane and hydrogen system), apply a year-long, hourly granularity (to capture the increasing volatile power system dynamics), consider all most-likely low-carbon technologies, and assess a number of scenarios and sensitivities that align with national and European decarbonisation objectives.

The joint modelling exercise could potentially be integrated into a more overarching approach, e.g. in the context of the preparation of the updated NECPs or network development plans (cf. the indicative Actions 7.2.13, 0, and 7.2.9, respectively, in the Annex, Section 7.2).

7 Annex – Actions

7.1 Mapping of observations, convictions and actions

Each conviction builds upon one or several observations from the scenario and literature review. And for each conviction, one or several exemplary actions were drafted in order to exemplarily illustrate how the convictions could be put into action, cf. Table 5.

Table 5 - Mapping of observations, convictions and actions

Topic	#Conv.	Conviction	Underlying observations	Suggested action(s)
CO2	5.1	Power sector decarbonisation by 2035	4.2.1	CO2.1 - Achieve a decarbonised Penta power sector by 2035 (cf. 7.2.1)
Supply	5.2	Renewables are the main pillar of decarbonisation	4.2.2, 4.3.4	RES.1 - Penta objectives for RES share in power generation (cf. 7.2.2)
				RES.2 - Joint training strategy for more skilled labour in the field of RES installations (cf. 7.2.3)
				RES.3 - Joint RES projects and frameworks (cf. 0)
				RES.4 - “RES made in Penta” initiative (cf. 7.2.5)
Demand	5.3	“Energy efficiency first” releases pressure from the power system	4.1.4	EE.1 - Penta building decarbonisation initiative (cf. 7.2.6)
	5.4	Direct electrification comes with immediate benefits	4.1.1, 4.1.2	Elec.1 - Trans-Penta EV charging network (cf. 7.2.7)
				Elec.2 - Joint objective for heat pump roll-out (cf. 7.2.8)

Topic	#Conv.	Conviction	Underlying observations	Suggested action(s)
	5.5	Decarbonised molecules will play a limited but crucial role	4.1.1, 4.1.3, 4.2.1, 4.3.1	Hydrogen.1 - Joint Penta Electrolyser Objective and Hydrogen Strategy (cf. 7.2.9)
	5.6	Hydrogen economy needs to be established now	4.1.3, 4.2.4, 4.3.5	Hydrogen.2 - Joint hydrogen import strategy (cf. 7.2.10)
Infra-structure	5.7	Power grid capacities need to increase substantially	4.3.2, 4.3.3	Grids.1 - Increase the Penta cross-border interconnection level (cf. 7.2.11)
				Grids.2 - Regular best practice sharing on distribution grids (cf. 7.2.12)
	5.8	A coordinated approach to energy system planning	4.2.4, 4.3.1, 4.3.4, 4.3.5	Planning.1 - Joint NECP scenario preparation (cf. 7.2.13)
				Planning.2 - Penta network planning initiative / Joint Penta network development plan (cf. 0)
				Planning.3 - Promote best practice recommendations for all future energy system/network modelling activities (cf. 7.2.15)
System stability	5.9	Flexibility - a key element of the energy transition	4.2.3	Cf. (Trinomics, Artelys, 2023)
	5.10	Additional power demand can and must be flexible	4.1.2, 4.1.5	DSF.1 - Penta smart demand initiative (cf. 7.2.16)
	5.11	Energy storage facilitates RES integration	4.3.1	Storage.1 - Joint Penta storage deployment initiative (cf. 0)
Markets	5.12	The transition requires a future-proof market design	Cf. (Trinomics, Artelys, 2023)	

7.2 Actions

This section lists all **indicative actions.** It is to be noted that the following list of actions has for purpose to provide examples. The list is to be understood as non-exhaustive. Individual actions require a dedicated impact and cost-benefit analysis before being put into practice.

All actions are individually described regarding the specific challenges and risks that need to be addressed, the overall concept (entitled *solution*), a more detailed indication of potential implementation (applying in particular to *strategies* and *procedures*), the related advantages and limitations, and finally a short list of related actions.

7.2.1 CO2.1 - Achieve a decarbonised Penta power sector by 2035

Topic: CO2	**CO2.1**	**Achieve a decarbonised Penta power sector by 2035**
Challenges/risks	- - -	Reaching **carbon-neutrality by 2050** requires significant transformations in all sectors of the economy However, some sectors feature hard-to-abate emissions and, in many cases, the only economically viable way of decarbonisation appears to be **direct or indirect electrification**, given that mature and cost-efficient technologies are available to decarbonise power supply Yet, **if power systems do not decarbonise sufficiently rapidly**, there is a major risk that the 2050 decarbonisation target is not met (as fossil energy carriers or carbon-intensive electricity are continuously used).
Solution	-	Concentrate efforts on **decarbonising the Penta power systems by 2035**[43], via massive deployment of RES and other low-carbon technologies and reducing the (inevitable) increase in long-term electricity demand to a minimum through energy efficiency measures.

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[43] This date is inspired by the G7 announcement from May 2022, cf. G7 (2022): G7 Climate, Energy and Environment Ministers' Communiqué; https://www.bundesregierung.de/resource/blob/974430/2044350/84e380088170c69e6b6ad45dbd133ef8/2022-05-27-1-climate-ministers-communique-data.pdf?download=1, indicating "we further commit to a goal of achieving predominantly decarbonised electricity sectors by 2035, prioritising, consistent with our 2030 NDCs, our power sector transition commitments and our respective net zero commitments, concrete and timely steps towards the goal of an eventual phase-out of domestic unabated coal power generation." The date is further backed by existing scenario assessments, such as Agora Energiewende (2022): Climate-neutral power system 2035; https://www.agora-energiewende.de/en/publications/climate-neutral-power-system-2035/ or Ember (2022): New Generation: Building a clean European electricity system by 2035; https://ember-climate.org/insights/research/new-generation/

	- As power systems will be increasingly interconnected, a common Penta commitment is crucial to create an environment that **enables the required investments and guarantees consistency/complementarity** of respective neighbouring national strategies. - Additionally, in an effort to further contribute to the economy's net-zero balance, power systems could aim for **negative emissions** targets by 2040, thereby providing room for residual emissions from hardest-to-abate sectors.
Implementation	**The building block consists of announcing such a target**, which could be adapted by changing the target year (+/- 2035), indicating full or predominant decarbonisation, announcing the target as being binding or not. See the related strategic building blocks further below.
Advantages/benefits	- Unlock system-wide decarbonisation by 2050 - Positions Penta as a leader in Europe, able to seize ambitious objectives (CTP) and enforce EU sectoral strategies
Barriers/limitations	- Might require an update of existing coal/gas phase-out strategies - 2035 is the day after tomorrow: only 13 years left to act => little room for manoeuvre / strong need for immediate action - Limited effectiveness of non-binding or vague (in the case of "predominant decarbonisation") targets
Link to other actions	Power supply and demand must be transformed in order to reach carbon neutrality by 2035. The following strategic building blocks can help to achieve this objective (amongst others): - Importance of coordination regarding national strategies, Planning.1 - Change in power supply mix via massive RES deployment, RES.1 - Facilitate power demand transformation via building stock thermal renovation, EE.1

7.2.2 RES.1 – Penta objectives for RES share in power generation

Topic: RES	**RES.1**	**Penta objectives for RES share in power generation**	
Challenges/risks	Based on available transition pathways towards carbon neutrality, variable RES will be the main power source in the Penta region towards 2050, and the key enabler of the decarbonisation of the power system. In order to reach the expected shares, unprecedented rates of deployment are required, and investments need to strongly speed up. - All national carbon neutral scenarios foresee high shares of wind and solar in 2050 (above 39% variable RES). Achieving such a RES penetration requires annual installations to significantly speed up. - Other technologies are available within Penta alongside the variable wind and solar production, notably bioenergy and hydro production.		

	o An extensive deployment of hydro resources reduces system costs and brings flexibility to the grid at the local level. Up to 9 GW (+8%) of additional reservoirs, run of river and pumped hydro storage capacity are expected in Penta by 2040[44]. - The national share of each technology will depend on countries' potential, historical choices and national strategies.
Solution	- Penta should announce a clear commitment RES as the main future energy source in the power production mix and indicate objectives for the mid-term and long-term horizon.
Implementation	- The possible common RES objective for the Penta region can be designed in different ways o In terms of annual investment levels (in GW), in terms of RES shares in power production or in terms of total RES power generation volumes ▪ The scenario analysis leads to the following RES target values: **57 %, 79 % and 93 % by 2030, 2040 and 2050**[45] ▪ The required RES deployment rates (incl. hydro and bio-energy) per year to reach these shares are: **28 GW/y, 36 GW/y, and 34 GW/y at the Penta level respectively from now to 2030, from 2030 to 2040 and from 2040 to 2050**[46]. o Covering only vRES (solar and wind), possibly with technology-specific targets, or RES generation as a whole (incl. hydro, biomass etc.) o The objective can be formulated as being binding/non-binding (possibly also depending on statistical transfers with other EU MSs)
Advantages/benefits	- Position Penta as a leader in Europe in its ambition of renewable energy development, able to shape national and supra-national targets. - Send a signal to investors that Penta countries believe in renewables as the main future power source.
Barriers/limitations	- Target setting should be aligned with NECP preparation, target setting in other initiatives (e.g. NSEC)

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[44] As stated in the Distributed Energy scenario of the TYNDP 2022.

[45] The figures are based on: "BEHAVIOUR" scenario of the BFE study for Belgium, S3 scenario of the Ademe study for France, Climate Neutral 2045 study published by Agora for Germany, "European" scenario of the Netbeheer study, Zero Basis scenario of the BFE Study for Switzerland, the Target scenario of the Luxembourg's NECP (2050 figures are projected), and the Austrian NECP (Austrian figures for 2050 are projected, assuming no fossil production by 2050). The Austrian NECP only gives production values, the Austrian deployment rate only includes wind and solar deployment rates, based on national wind and solar availabilities.

These target shares for 2030 and 2040 are consistent with the 2035 decarbonisation target. In 2030 and 2040, the target shares of fossil thermal generation are respectively 17% and 6%, and the shares of nuclear production are 24 and 14% (for the same selection of scenarios). A linearisation of the 2030 and 2040 values leads to about 200 TWh of fossil thermal generation in 2035, mostly gas. Using the gas emission factor, the carbon content of the electricity produced is around 28 gCO2/kWh in 2035.

Bundesministerium für Wirtschaft und Energie (BMWi) (2022), Langfristszenarien für die Transformation des Energiesystems in Deutschland

[46] Current data are based on 2020 figures for Switzerland, Belgium, Austria, Luxembourg, on 2019 data for France, on 2018 data for Germany, and on 2015 data for the Netherlands.

Link to other actions	This acceleration in renewables deployment needs to be supported by a solid policy from Penta, notably to increase Penta's expertise in the RES manufacturing and installation: - The training of a skilled labour in the field of RES installations (RES.2) - The manufacturing of renewable technology within Penta (RES.4) - Joint RES projects and frameworks; if the objective is announced in terms of annual installation volumes, this could be linked to RES capacities that are jointly tendered across the entire Penta region (RES.3)

7.2.3 RES.2 - Joint training strategy for more skilled labour in the field of RES installations

Topic: RES	**RES.2**	**Joint training strategy for more skilled labour in the field of RES installations**	
Challenges/risks	- RES installations need to be substantially accelerated, yet lack of skilled labour represents one major barrier in the coming years - “In the EU, 650,000 people work in wind and solar energy. This figure is set to double in the next eight years, according to trade associations SolarPower Europe and WindEurope [...] For solar and wind, most workers are involved in the installation of panels and turbines, meaning they work through a pipeline of projects and move on every few months, often to different countries.”.[47] - “Europeans report delays of up to a year to install solar rooftop systems, and even longer if combined with battery storage or heat pumps. [...] Our forecast shows solar (PV) jobs on a steady rise in 2022 too, with an anticipated 14% annual growth to about 530,000 FTEs under the Medium Scenario’s 34 GW capacity additions. However, if the 40 GW High Scenario becomes reality, we will see jobs increasing by 30% to 606,000.”[48]		
Solution	- A joint strategy across Penta countries to accelerate the training of skilled labour and make the related job environment more attractive		
Implementation	- Exchange on experiences to speed up the training process and make the respective jobs attractive - Joint monitoring of need for upskilling and training programmes - Coordinated training programs and grades (at least at the regional level, e.g. between LU/DE, LU/FR/BE, BE/NL, NL/DE) o Link the training to undergraduate degrees and international exchange programs (such as Erasmus)		

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[47] S&P Global (2022): Skills shortage imperils global energy transition; https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/skills-shortage-imperils-global-energy-transition-71565735

[48] SolarPowerEurope (2022): EU Solar Jobs Report 2022; https://www.solarpowereurope.org/insights/thematic-reports/eu-solar-jobs-report-2

	- Establish a joint strategy with non-EU/third countries, to train their residents (similar to comparable approaches in the healthcare sector) and invite them to work in the Penta countries for a certain time, before they return working on the energy transition in their home countries - Aligned regulation on working permits etc. to facilitate even further the free movement of labour
Advantages/benefits	- A coordinated approach across Penta would allow trained staff to work easily in different Penta countries,
Barriers/limitations	- National regulations make a coordination approach very difficult to be implemented - Approach at the EU level might be more relevant (but also much more time consuming); to be linked to the EU large-scale skills partnership
Link to other actions	- The main driver behind such an initiative would be a common RES target (cf. RES.1) - Similar strategy conceivable for the buildings sector (cf. EE.1)

7.2.4 RES.3 - Joint RES projects and frameworks

Topic: RES	**RES.3**	**Joint RES projects and frameworks**	
Challenges/risks	- RES investments and installations need to speed up - Permitting is one major bottleneck - Not all countries dispose of very favourable solar/wind/hydro potentials (e.g. no offshore wind for AT, CH, LU)		
Solution	- REDII suggests a number of mechanisms that EU MS / Penta countries could actually make use of to accelerate installations and steer investments to the most cost-efficient RES potentials		
Implementation	- The following options are included in **REDII** and could be subject to implementation/application in selected/all Penta countries o Art. 5, Opening of support schemes for electricity from renewable sources; NB: Art 15.5 states "By 2023, the Commission shall carry out an evaluation of the implementation of this Article. That evaluation shall assess the need to introduce an obligation on Member States partially to open participation in their support schemes for electricity from renewable sources to producers located in other Member States with a view to a 5 % opening by 2025 and a 10 % opening by 2030." o Art. 8, Union renewable development platform and statistical transfers between Member States[49] o Art. 9&10 (and 11), Joint projects between Member States (and third countries)		

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[49] Luxembourg made already use of transfers of excess renewable energy from Estonia and Lithuania for instance (COM(2019) 225 final - Renewable Energy Progress Report). The Netherlands used a statistical transfer of renewable energy from Denmark to meet their targets.

	o Art. 13, Joint support schemes o NB: The proposal for the amendment of REDII[50] suggests an obligation for Member States to test cross-border cooperation within the next 3 years. - Other options to create a **harmonised framework for RES investments**: o Make enhanced use of the **Renewable Energy Financing Mechanism** (REFM)[51] o Front-load the **EU's Solar Rooftops Initiative**, an obligation to install solar on all new public and commercial buildings by 2026/2027 and all new residential buildings by 2029[52] o Acceleration and simplification of the **permit-granting process**; possibly harmonisation/streamlining of certain procedural requests across Penta countries to facilitate the permitting process to investors o Pilot projects (within Penta) on **guarantees of origin** featuring a sub-hourly time stamp allowing for close-to-real time validity, hence generating more representative GO price signals[53]
Advantages/benefits	- A coordinated implementation entails significant coordination efforts among Penta countries
Barriers/limitations	- Cross-border streamlining of permit granting difficult to implement due to national legislative and regulatory peculiarities
Link to other actions	- Such a joint RES approach should be accompanied by a joint (strategic or grid) planning process, cf. Planning.1 and Planning.3

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[50] European Commission (2021): Proposal for a directive of the European Parliament and of the Council amending Directive (EU) 2018/2001, COM(2021) 557 final; https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0557

[51] The REFM is a bottom-up mechanism, based on voluntary participation from Member States, based on Article 33 of the Governance Regulation (EU) 2018/1999, and that is in force since January 2021. It is a match-making mechanism where contributing countries fund a European fund for EU-wide tenders. Contributing countries can specify how their money should be used (e.g., technology-specific). Projects are developed in host countries, and statistical transfers are delivered to the contributing country for the renewable electricity produced in the host country.

[52] European Commission (2022): EU Solar Energy Strategy, COM(2022) 221 final; https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A221%3AFIN&qid=1653034500503

[53] For further reading, see for instance Trinomics et al. (2021): Technical support for RES policy development and implementation: delivering on an increased ambition through energy system integration (page 208ff); https://op.europa.eu/en/publication-detail/-/publication/6fcc38cb-1440-11ec-b4fe-01aa75ed71a1/language-en

7.2.5 RES.4 - “RES made in Penta” initiative

Topic: RES	**RES.4**	**“RES made in Penta” initiative**
Challenges/risks	- - -	Energy import dependency does not only concern energy carriers but also energy equipment; a too strong dependency from non-EU imports puts at risks the accelerated deployment of RES RES (and other key energy technologies, like batteries) require raw materials and rare earths in particular; recycling, short-distance transports, circular economy need to gain momentum Production of key energy technology equipment is to happen in a sustainable, fair manner; yet, it is difficult to control entire (global) supply chains
Solution	-	Establish a RES made in Penta initiative aiming at boosting the share of future solar/wind installations to be manufactured domestically (or at least inside the EU)
Implementation	- -	Facilitate the installation of RES equipment production capacities in the Penta region (and the EU) via: o Creation of a safe/attractive investment environment o Establish training programs to ensure the availability of skilled labour o Provide priority access to raw materials via coordinated exploitation of raw material resources within the Penta region (e.g. lithium[54]) and coordinated import strategies o Establish a comprehensive, universal recycling program (e.g., for wind turbine blades,) o Assist with a holistic R&D program o Push for CBAM Potentially to be linked to the EU’s Just Transition program/mechanism
Advantages/benefits	- -	Decrease the dependency on other countries, even in terms of power generation equipment imports Relocate part of the value added linked to the manufacturing process to the Penta countries
Barriers/limitations	- - -	Shortage on skilled labour might hamper the objective to materialise (cf. RES.2) Compliance with WTO rules needs to be ensured Potential interference with CBAM
Link to other actions	-	To be designed in coordination with RES.2

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[54] https://www.euronews.com/green/2022/10/24/frances-massive-new-mithium-mine-could-supply-700000-electric-car-batteries-a-year

7.2.6 EE.1 - Penta building decarbonisation initiative

<table>
<tr><th>Topic: EE</th><th>EE.1</th><th>Penta building decarbonisation initiative</th><th></th></tr>
<tr><td>Challenges/risks</td><td colspan="3">Buildings account for 40% of final energy consumption in the Union and 36% of its energy-related greenhouse gas emissions. All available transitions pathways towards carbon-neutrality rely extensively on thermal renovation of the building stock. Thermal renovation facilitates the deployment of heat pumps (which work most efficiently in buildings with low heating inlet temperatures) and, in case of direct and indirect electrification of heating, relieve power demand increase and thus reduce pressure on power systems.
Penta countries have transposed the Energy Performance of Buildings Directive (EPBD, 2018/844/EU) to varying degrees and in different ways. However, still seems to be far from delivering its contributions to the decarbonisation of the energy systems, for various reasons (non-exhaustive list)[55]:
- Very heterogenous implementation how Energy Performance Certificates (EPCs, EPBD, Art. 12) are issued, with varying benefits
- Heterogenous, uncoordinated and insufficiently concrete Long-Term Renovation Strategies (LTRS, EPBD, Art. 2a)
- Lack in skilled labour may hamper the renovation wave and the installation of heat pumps[56]
Missing thermal renovation requirements would make countries fail their decarbonisation objectives.</td></tr>
<tr><td>Solution</td><td colspan="3">Penta can establish a joint building renovation strategy, promoting a coordinated implementation of the requirements under the EPBD and by cooperating on training programmes with its members in order to ramp up building renovation</td></tr>
<tr><td>Implementation</td><td colspan="3">- Penta to organise a consultation on members’ Long Term Renovation Strategies, envision a coordinated LTRS development and commit to their upgrade into “Building renovation plans”, as stated by the EPBD.
- Ensure/promote alignment between national targets, progress and success indicators
- Exchange of best practices in the issuance of EPCs and their utilisation as precondition for rental/sales etc.[57]
- Once renovation standards are sufficiently aligned, Penta to set-up a joint training program for job profiles related to building renovation and (low-carbon) heating installations
  ○ Coordinated training programs and grades (at least at the regional level, e.g. between LU/DE, LU/FR/BE, BE/NL, NL/DE)</td></tr>
</table>

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[55] See for instance European Parliament (2021): Draft report on the implementation of the Energy Performance of Buildings Directive, https://www.europarl.europa.eu/doceo/document/ITRE-PR-695323_EN.pdf

[56] See for instance Euractiv (2022): EU confronted with lack of skilled labour to support building renovation wave; https://www.euractiv.com/section/energy-environment/news/eu-confronted-with-lack-of-skilled-labour-to-support-building-renovation-wave/

[57] See for instance the most recent announcements from France: https://www.frenchentree.com/french-property/selling-homes/french-property-need-to-know-energy-performance-certificates/

	o Establish a joint strategy with non-EU/third countries, to train their residents (similar to comparable approaches in the healthcare sector) and invite them to work in the Penta countries for a certain time, before they return working on the energy transition in their home countries o Aligned regulation on working permits etc. to facilitate even further the free movement of labour
Advantages/benefits	- Reduces deployment costs due to best practices sharing and free movement of labour - Position Penta countries as a leading example regarding thermal renovation in Europe
Barriers/limitations	- National regulations make a coordination approach very difficult to be implemented - Joint training approach at the EU level might be more relevant (but also much more time consuming) o Position Penta's action as a facilitator to the EU's strategy success o An earlier EU initiative for skilled labour existed, "Build up skills", existed; to be verified to what extent this initiative is still ongoing[58] - Best-practice exchange platform already exists: https://epbd-ca.eu/about-us
Link to other actions	- Similar to joint training initiative for RES installations, RES.2 - Accelerated and efficient building renovation will foster massive Penta-wide heat pump roll-out, see Elec.2

7.2.7 Elec.1 - Trans-Penta EV charging network

Topic: Elec	**Elec.1**	**Trans-Penta EV charging network**	
Challenges/risks	- Risk that different motor technologies are developed in parallel for private road passenger transport (electric, fuel cell, synthetic fuels) => risk of split efforts (in terms of investments in refuelling infrastructure but also in cars) resulting in diffuse signals for consumers which technology to invest in and in stranded assets for refuelling infrastructure operators - EVs still struggle with limited ranges and difficulty to ensure long-distance travels		
Solution	- A clear **commitment of Penta in favour of battery EVs** (no hybrids), in contrast to other propulsion technologies, to steer investments in one direction - Joint establishment of a **Penta-wide EV (fast) charging network**: get from Vienna to Brest or from Interlaken to The Hague without losing hours in recharging your car		
Implementation	- Different levels of ambition in the design of the strategy are possible		

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[58] Cf. for instance the Dutch implementation of the initiative: https://buildupskillsnederland.nl/english/

	o Announce a number of public (fast) charging to be installed by 2030/40 across the entire Penta region ▪ This infrastructure should be adapted to the growing share of EV within Penta: 2 – 7% of the vehicle stock in 2025, 7 – 19% in 2030, 34 – 53% in 2040, and 54 – 89% in 2050[59] o Envision a Trans-Penta EV charging network: identify key corridors to be equipped with fast charging stations by 2025 o Joint procedure in the charging infrastructure roll-out (e.g. joint public tenders) o Develop of a joint infrastructure and funding gap analysis - Additional options are available in a 2021 report from the European Court of Auditors[60]
Advantages/benefits	- Clear signal in favour of one specific technology, which reduces uncertainty for investors and consumers
Barriers/limitations	- Promoting such a trans-Penta EV charging network discredits/disadvantages alternative options o A long-distance highspeed/night train railway network => could be an alternative building block o Carsharing/carpooling (potentially increasingly relevant if autonomous vehicles materialise – even on long distance tracks) - Coordination should be sought with other EU countries, the European Commission - A pure focus on passenger cars (disregarding refuelling needs for light duty vehicles, trucks etc.) might result in redundant infrastructure => joint approach required - The actual problem for long-distance travelling is actually the comparative price advantage of (low-cost) flights compared to train rides, notably due to lower taxes/levies on plane tickets => could be an alternative lever and building block to facilitate a modal shift from planes to trains
Link to other actions	- Links also to the exploitation of demand side flexibility, cf. DSF.1

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[59] The figures are based on the TYNDP 2022, weighted by the number of vehicles in each Penta country in 2020 (source: Eurostat). The minimum of the range is based on the Global Ambition scenario, the maximum is based on the Distributed Energy scenario. In total within Penta (excluding Switzerland), the vehicle stock amounted to 106 million vehicles in 2020.

[60] European Court of Auditors (2021): Infrastructure for charging electric vehicles: more charging stations but uneven deployment makes travel across the EU complicated; https://op.europa.eu/webpub/eca/special-reports/electrical-recharging-5-2021/en/

7.2.8 Elec.2 - Joint objective for heat pump roll-out

Topic: Elec	**Elec.2**	**Joint objective for heat pump roll-out**	
Challenges/risks	The buildings sector can primarily be decarbonised via direct electrification (supported by a low-carbon power generation mix) with heat pumps as the key technology of the future decentralised heat supply in buildings and for part of the industry (low-/medium temperature). However, this is **not yet a general consensus** and in particular certain industry lobbies aim to push the use of hydrogen in the buildings sector.		
Solution	- The definition of a **Penta-wide heat pump roll-out objective/pathway** for the years to come		
Implementation	- The objective could be defined in terms of the total number of heat pumps installed annually, in total, or as share of total energy demand for heating, for selected target years o Penta countries to aim at **1 to 1.5 million** new heat pump installations per year from now to 2040[61]. - Penta to support the sharing of good practices for the management of heat pumps power demand, and the exchange on a consistent modelling of their impact on the dynamics of the energy system		
Advantages/benefits	- A strong commitment from Penta towards this technology solution compared to other heat generation technologies would create confidence in the technology, send a signal to technology manufacturers, incentivise home owners to invest and end the debate on the potential contribution from hydrogen-fuelled heating systems[62] - Reduce the dependence of household bills on fossil fuels, and reduce CO2 emissions from the residential sector[63] - The use of heat pumps is manifold: o Heat pumps are more than 5 times more energy-efficient than green hydrogen boilers[64] o If linked to a local thermal storage, they can bring flexibility to the energy system. They can offer demand-side flexibility if they are operated in a smart manner. o In the industry, heat pumps can cover low and medium temperature heat demand; a Penta-wide target and heat pump roll-out may also favour the technology evolution of heat pumps		
Barriers/limitations	- Heat pump deployment is particularly feasible and profitable in new and renovated buildings => needs to be aligned with a renovation strategy and ambitious building standards - The present building block focusses on decentralised heat pumps in residential/commercial buildings; a dedicated building block for large-scale heat pumps in industry and district heating networks could be added		
Link to other actions	- Supporting building renovation (EE.1) facilitates heat pump deployment and avoids over-dimensioning of heat pumps. - The deployment of heat pump can offer demand-side flexibility (cf. DSF.1).		

7.2.9 Hydrogen.1 - Joint Penta Electrolyser Objective and Hydrogen Strategy

Topic: Hydrogen	**Hydrogen.1**	**Joint Penta Electrolyser Objective and Hydrogen Strategy**	
Challenges/risks	- Each Penta country disposes of an individual, national H2 strategy which were not necessarily designed in a concerted approach - The Penta region is considered to be the initial building block of the EU H2 backbone (cf. graph below)[65]; make this initial H2 network materialize in a timely manner requires a coordinated approach (in particular addressing investment needs in electrolyser and cross-border power/H2 network infrastructure)		

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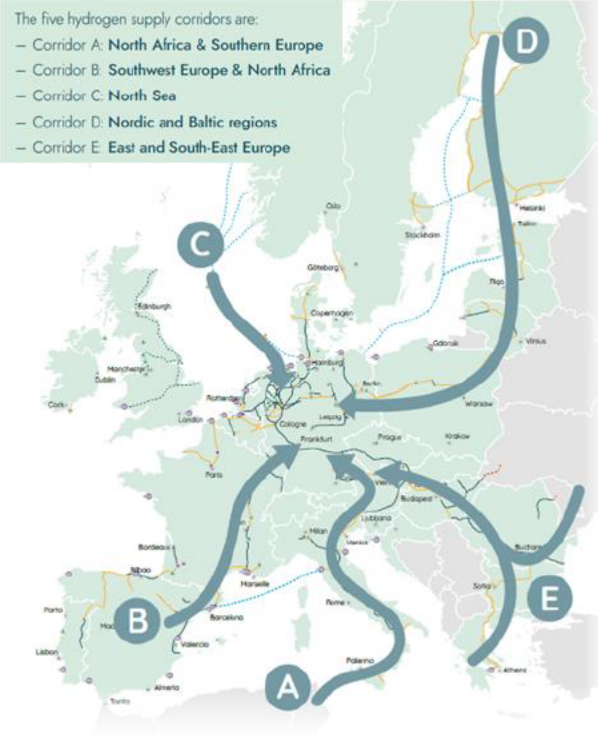
[61] The minimum value is based on the German projected installation rate in the Agora's study Climate neutral 2045, and the maximum value on the installation rate aimed by the UK. The figures are extrapolated to the rest of Penta based on the respective Penta country's population. The Agora study forecasts a drop in annual installations from 2040 onwards.

[62] Notably, the Austrian government has communicated a clear prioritization in the hydrogen uses, notably excluding its use in heating systems (cf. https://www.euractiv.com/section/energy/news/austrias-new-hydrogen-strategy-slams-use-in-heating-transport/).

[63] In the UK, the coordinated deployment of heat pump is estimated to lead to a potential cost reduction of at least 20% (cf. https://www.gov.uk/government/news/boost-for-innovative-heat-pump-projects-to-drive-cleaner-heating)

[64] David Cebon (2022): Hydrogen for heating? A comparison with heat pumps (Part 1), https://h2sciencecoalition.com/blog/hydrogen-for-heating-a-comparison-with-heat-pumps-part-1/

[65] Some cross-border hydrogen pipelines already exist, yet being owned by private operators (e.g. Air Liquide)



Guidehouse (2021): European Hydrogen Backbone, https://guidehouse.com/insights/energy/2021/connecting-supply-with-demand-through-the-ehb

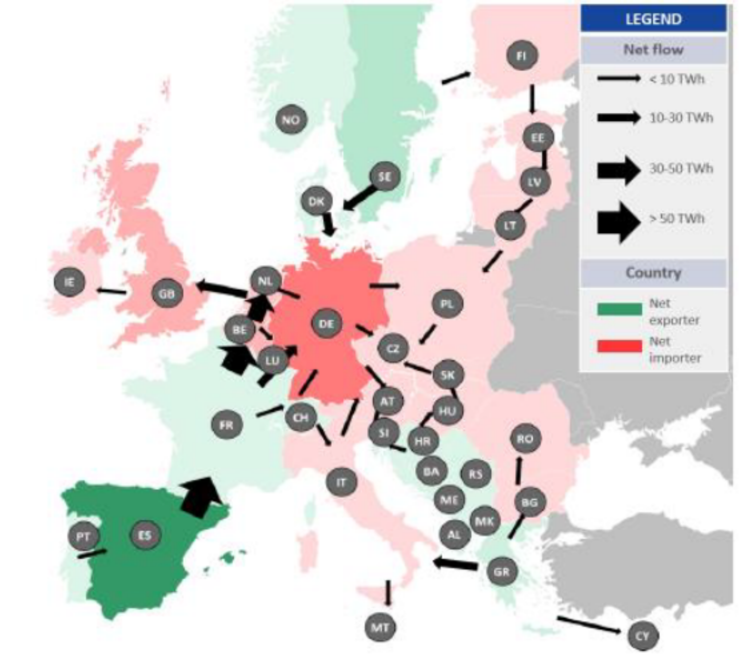


Figure 5-4: Cross-border hydrogen flows, scenario H2-A optimised

Artelys (2021): METIS study on costs and benefits of a pan-European hydrogen infrastructure, https://op.europa.eu/en/publication-detail/-/publication/c50a12fc-5eeb-11ec-9c6c-01aa75ed71a1/language-en

- Risks of inaction consist of H2 supply deficits, stranded assets (construction of H2 facilities at places where they are ultimately not needed), delay in the uptake of H2 supply, storage and interconnection capacities

Solution	Several options may be envisioned: - Formulate a **joint electrolyser deployment objective** at the Penta level

	- Define a **Joint Hydrogen Strategy**
Implementation	The **Penta electrolyser objective** could for instance aim for 25 to 30 GW by 2030[66]. National strategies of Penta countries released so far aim for a total of 20 to 27 GW of green electrolyser capacity by 2030[67] and between 75 GW and up to 135 GW by 2050. Such an objective could have a binding/non-binding character, be expressed in terms of GW, TWh or share of green H2 in total H2 demand. The **Joint Hydrogen Strategy** may contain the following elements, varying in terms of commitment, ambition and concreteness: - Agree on no-regret **priority end-uses** that should switch to green hydrogen[68] and that drive future hydrogen demand - Identification of major **hydrogen consumption centres** (for instance cross-border H2 clusters in the Rhine valley) - Identify **priority corridors** for cross-border H2 transmission along **priority locations** for H2 consumption centres, electrolyser facilities, major RES injection sites as well as key hydrogen transit connections - Include a detailed **timeline** for the rollout of H2 infrastructure by 2025/30/35/40 - Explicit the **optimal trade-off** between exploitation of best-performance RES potentials, electrolyser siting and H2/power grid expansion (cf. also Planning.1) - Launch of **industrial partnerships** at the Penta level: pilot projects, electrolyser/steel imports or production - Assess **national objectives**; check coherence with the joint vision by building upon joint scenario development; derive (non-binding?) minimum objectives, timeline etc. (cf. also Planning.1)
Advantages/benefits	- Initiate the build-up of a hydrogen system => create investor security - in a coordinated, cost-efficient manner, avoiding stranded assets and ensuring coherence in the build-out
Barriers/limitations	- High degree of uncertainty on the need/potential/location of domestic H2 production and hydrogen interconnection capacities vs. H2 production in other (more favourable parts) of Europe and beyond; dedicated planning approach would be required, cf. Planning.1, Planning.2 - Limited effectiveness of non-binding targets

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[66] The European Commission's REPowerEU plan envisions 10 Mt of domestic green H2 production by 2030, which translates into some 65 to 80 GW of electrolyser capacity, cf. also IEA (2022): Global Hydrogen Review 2022; https://www.iea.org/reports/global-hydrogen-review-2022

[67] The following 2030 green H2 production targets are announced in the Penta countries so far: AT 1 GW, DE, 10 GW, FR 6.5 GW, NL between 3 and 4 GW, possibly to be doubled (cf. https://nltimes.nl/2022/04/13/ruling-parties-want-double-netherlands-green-hydrogen-production). No target available for CH; doubts about domestic H2 production in BE.

[68] This may also include the definition of No-Go-options for H2, as suggested for instance by the Austrian Hydrogen Strategy: https://www.euractiv.com/section/energy/news/austrias-new-hydrogen-strategy-slams-use-in-heating-transport/

	- H2 strategy requires coordination with RES expansion, in particular w.r.t. offshore wind capacities => to be linked to the NSEC 2050 vision[69]? - Important to ensure compatibility with the IPCEI process
Link to other actions	- Penta countries should coordinate on future hydrogen end-uses. Notably, passenger road transport and residential heat supply will be subject to direct electrification (Elec.1, Elec.2) - Penta hydrogen strategy should be consistent with respective NECPs, cf. Planning.1

7.2.10 Hydrogen.2 - Joint hydrogen import strategy

Topic: Hydrogen	**Hydrogen.2**	**Joint hydrogen import strategy**	
Challenges/risks	**Imports of green hydrogen** are foreseen as a must-have complement to domestic, low-carbon power-based generation in the Penta region, in order to further decarbonise the economy without adding too much pressure on power systems and resources. H2 imports from outside the Penta region and even from outside the EU are thus very likely to be necessary (at least from 2030 onwards). On average across available figures for Germany, Netherlands and Switzerland, projected import volumes meet two third of the total hydrogen demand.[70] Two hydrogen **import options** exist for the import of hydrogen: - Import of gaseous hydrogen by pipeline from countries in closer geographical proximity to Penta and the EU (Eastern Europe, Asia, MENA region) - Import of liquefied hydrogen, or its derivatives (most notably, ammonia, synthetic methane, methanol, and liquid organic hydrogen carriers, LOHC) via shipping Each of these options offers its own benefits and disadvantages, and the trade-offs between these options have yet to be addressed. Locally, the import choice will depend on the volumes of imports needed, the distance to the export location, the end uses of hydrogen (affecting the cost			

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[69] NSEC (2022): Joint Statement on the North Seas Energy Cooperation; https://energy.ec.europa.eu/system/files/2022-09/220912_NSEC_Joint_Statement_Dublin_Ministerial.pdf

[70] The projected volume for Germany is an average across volumes from the Climate Neutral 2045 study published by Agora, and from the TN-H2 and TN-Strom scenarios published by BMWK. The volume for the Netherlands is calculated as an average across the European and International scenarios published by Netbeheer.

	competitiveness with alternative energy carriers, e.g. direct electrification), and on the future economic and technical evolution of each of these options. The risks of an **insufficient cooperation regarding hydrogen imports** within Penta are an enhanced competition with other Penta members, reduced lever for negotiations, delayed/uncoordinated import infrastructure build-out (inconsistent hydrogen carrier choices, implications on import terminals and pipelines, notably).
Solution	- Penta to coordinate on hydrogen imports; develop a **joint hydrogen import strategy**
Implementation	- Establishing a joint hydrogen strategy would require a **coordination between Penta members** on ○ **Import needs** (volumes and dynamics), ▪ Jointly evaluate how H2 demand is expected to evolve (applying similar assumptions on no-regret hydrogen use cases and "hydrogen No-Gos", e.g. in individual passenger road transport or decentralised heating), to what degree H2 demand can be met by indigenous Penta H2 production capacities and how much imports are required. ▪ Based on the literature review, the need for H2 import could reach 430 to 540 TWh_H2[71] by 2050. ○ Identification of most promising **partnerships** with hydrogen export countries ▪ Identifying high-potential exporting countries (high potential in terms of costs, potentials and political stability), and common import routes ▪ Distribute responsibilities for liaising with exporting countries ▪ Establish long term contracts with specific exporting countries (and potentially Penta as a whole) ○ **Import infrastructure strategy** (coordination between coastal/continental countries), ▪ Based on the identification of common import routes, quantify specific import infrastructure deployment needs, notably regarding shipping vessels, import terminals, storage facilities nearby terminals, and pipelines (cross-border and internal) ▪ Evaluate the need to cooperate with third countries on infrastructure expansion

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[71] This figure was built from the annual hydrogen demand in 2050 within Penta (from the TYNDP Distributed Energy scenario, and from the PSI CLI scenario for Switzerland) and the import shares indicated in the national scenarios (Agora KN2045, TN-H2 and TN-Strom from the BMWi study for Germany, the European and International scenario from the Netbeheer study for the Netherlands, and the CLI scenario from the PSI study). The range is built based on the national lowest and highest ranges projected in these scenarios.

These import volumes are figures for 2050. However, some Penta countries may have to import by 2030. The agora study foresees a need for imports as early as 2030 (70% of the hydrogen demand is imported, i.e. 44 TWh and 158 TWh imported in 2030 and 2040 respectively). The need for imports in Belgium is also seen as significant, and could develop in the coming decades.

	▪ Ensure a fair allocation of terminal/port adaptation costs
Advantages/benefits	- Effort sharing in the establishment of strategic partnerships - May be coupled to (existing/planned) development aid projects - Coordinating imports in a joint way makes it possible to gather large volumes of imports, thus lowering costs by mutualising the costs of the various import steps
Barriers/limitations	- A strategy at the EU level could make even more sense o By engaging in such a joint Penta strategy, Penta could actually pave the way for an EU strategy - High degree of uncertainty on the evolution of required import volumes, uncertainty on the best technological option for hydrogen import - The choice to import hydrogen raises questions about energy dependence from other countries[72].
Link to other actions	- The hydrogen import strategy would ideally be designed based on the joint NECP analysis (Planning.1) and integrates the Hydrogen strategy (Hydrogen.1) - The hydrogen import strategy affects networks needs and should be considered in network planning (cf. Planning.2)

7.2.11 Grids.1 - Increase the Penta cross-border interconnection level

Topic: grids	**Grids.1**	**Increase the Penta cross-border interconnection level**	
Challenges/risks	- Decarbonisation of power systems requires to rely extensively on RES. Yet, RES potentials are not evenly distributed among Penta countries. While there is a trade-off between the exploitation of high-performance RES and power grids expansion, ensuring cost-effectiveness at the Penta power system scale will only be possible with **enhanced cross-border power flow capacities**. - Additionally, the increasing shares of RES in power mixes will lead to both short and long-term power supply variations implying **flexibility needs**: daily variations in areas with high PV shares, weekly/monthly fluctuations in areas with higher wind shares, seasonal variations in all cases, with geographical specificities: winter power surplus in Northern, more windy areas, summer power surplus in Southern, more sunny areas.		

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[72] This issue is raised in the RTE study. The study mentions that a number of stakeholders consider that maintaining an important share of dependance from other countries is not desirable.

- **Hydro power storage** potentials are concentrated in some of the Penta countries only[73]. Making these potentials available to all Penta countries requires enhanced levels of electricity interconnection.
- Finally, the internal electricity market cannot yet be considered as fully integrated, not even within the CWE market area, with (day-head) **price convergence** (i.e., difference <1 €/MWh) most recently stagnating around 50% and dropping to low levels in particular in winter time when power systems need to cope with higher demand levels (cf. graph below[74]).

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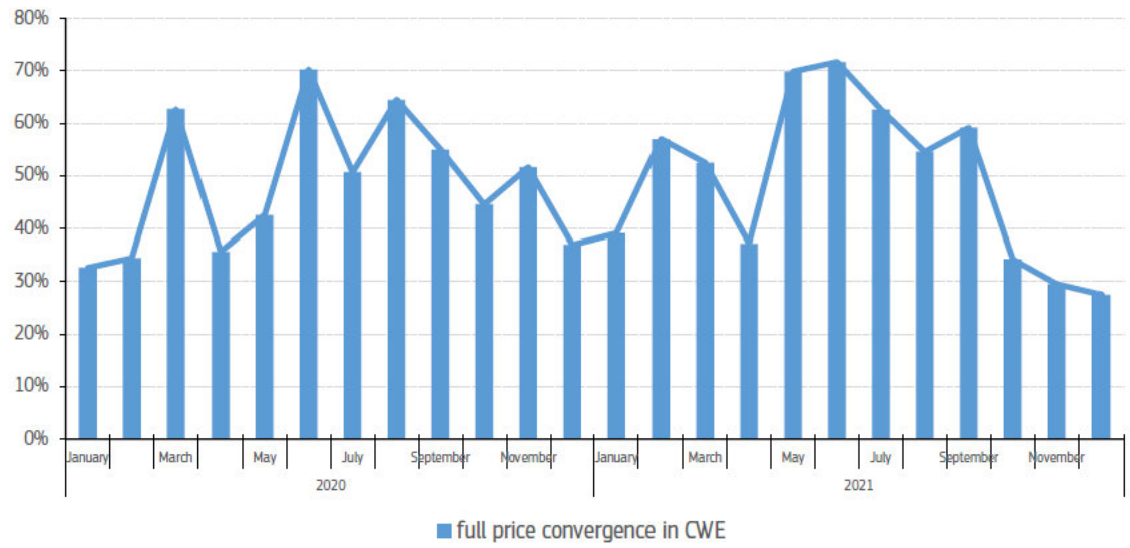
[73] See for instance Artelys et al. (2020): Study on energy storage – Contribution to the security of the electricity supply in Europe; https://energy.ec.europa.eu/study-energy-storage_en

[74] European Commission (2022): Quarterly report on European electricity markets; https://op.europa.eu/o/opportal-service/download-handler?identifier=a6eba083-932e-11ea-aac4-01aa75ed71a1&format=pdf&language=en&productionSystem=cellar&part=

Figure 31 – Monthly full price convergence in the CWE region in 2021 and 2020



Source: ENTSO-E

Solution

Enhanced power exchanges are reckoned as the most cost-efficient means of reducing flexibility needs, facilitating the sharing of flexibility resources, solving deficit and excess situations on the two sides of a border, and enabling a cost-optimal deployment of RES potentials.

⇨ **Set an objective for the extension of cross-border interconnections** between Penta member countries.

Implementation

- The definition of an objective requires in a first step, the **identification of the needs** for cross-border interconnection reinforcements based on a joint assessment
- The **objective** could be expressed in different metrics:
    - Increase in the overall cross-border interconnection capacity in % or +x GW (not necessarily applied to each bilateral interconnection but to the interconnections as a whole)[75]

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[75] TYNDP 2022 scenarios envision an increase of interconnection levels between Penta countries by 2050 by 33 to 37%, or 23 to 27% excl. PCIs, by comparison to current levels.

	○ Increase in the price convergence between countries - The objective should be leveraged by the **ACER Cross-border Cost Allocation** mechanisms to foster effective and fair project commissioning and asset operation - Finally, the objective could be complemented by a **commitment** of all Penta countries to keep interconnection capacities to a maximum available[76]
Advantages/benefits	- Ensure minimal system costs are reached - Increase interdependency of Penta countries and robustness of the Penta system
Barriers/limitations	- Ensure developments are consistent with EU strategies and the PCI process - Avoid that interconnection between Penta countries is optimal but internal bottlenecks (e.g. inside DE) persist making power flows bypassing via cross-border interconnections; internal flows are just as important.
Link to other actions	- The setting of an interconnection target touches upon other building blocks: ○ the integrated Penta transmission system planning, see Planning.2 ○ the joint Penta NECP preparation, see Planning.1 ○ Storage resource allocation, see Storage.1

7.2.12 Grids.2 - Regular best practice sharing on distribution grids

Topic: grids	**Grids.2**	**Regular best practice sharing on distribution grids**	
Challenges/risks	- **Power distribution grids** will face new challenges as increasing distributed generation capacities will connect and demand volumes and dynamics will evolve. Both the development of solar and wind generation, whose parks are more spread out over the territory, and mostly connected to the distribution network, and the electrification of consumption, require the **electricity distribution grids to be extended**, **reinforced**, and adapted to new dynamics. - Figures for carbon-neutral scenarios for France and Germany show that **annual costs of distribution networks could up to double** by 2050.		

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[76] In contrast to the announcement from Norway in Summer 2022 to reduce power exports, cf. https://www.reuters.com/article/norway-electricity-hydropower-idUKL8N2ZK4EJ

Solution	- As distribution grids reinforcement projects are local, cooperation between Penta countries is mainly expected for the **sharing of innovative and successful implementations**. A sharing of best practices between the Penta countries on the way how to mitigate and plan the need for distribution grid reinforcement appears as a key way to facilitate these local transformations.
Implementation	- **Two options** may be envisioned at the Penta level to cope with the identified challenges- o Penta countries to exchange experiences and coordinate regarding options to **mitigate these reinforcement needs**, notably: ▪ Supporting the development and utilisation/activation of local flexibility (e.g., storage technologies, a local district heating and cooling networks, distributed demand side flexibility (e.g. from heat pumps and EVs, incl. V2G) ▪ Balancing through local production ▪ Enabling signals (e.g. dynamic grid tariffs) to incentivize adaptation in local production and consumption (e.g. via smart charging); establishment of local flexibility markets o Penta countries to exchange experiences and coordinate regarding options to **realise distribution grid reinforcement** in the most cost-efficient and timely manner ▪ Enhanced grid planning procedures - Information exchange could happen via an **annual workshop with DSOs** to share successful national implementations. o The meeting could gather the following participants: representants from the largest DSOs within Penta, additional representants from DSOs that have implemented innovative pilot projects, and, possibly representants from E.DSO (European Distribution System Operators), potentially also involving TSO representatives (flexibility sharing, contrasting interests)
Advantages/benefits	- Encouraging internal communication allows actors to discover projects and methods of action with which they have little experience.
Barriers/limitations	- Initiative might overlap with the mission of E.DSO - The DSOs have specific local constraints, not all pilot projects can be generalised.
Link to other actions	- Demand side flexibility (DSF.1) - Storage (Storage.1)

7.2.13 Planning.1 - Joint NECP scenario preparation

Topic: Planning	**Planning.1**	**Joint NECP scenario preparation**
Challenges/risks	Direct and indirect electrification will strongly drive-up electricity demand: national scenarios foresee 60% to 90% demand increase at the Penta level[77]. This requires an adequate planning of electricity/H2 supply/conversion capacities and cross-border interconnection as well as storage infrastructure (cf. network planning, Planning.2). The major challenge arising at the regional/Penta level is to **determine the cost-optimal trade-off** between the exploitation of domestic vs high-performance RES potentials, electrolyser and hydrogen storage siting and minimized grid expansion across the entire Penta region. However, so far **National Energy and Climate Plans** (NECPs[78]) were primarily drafted in a rather isolated manner for each individual MS, without major cross-border coordination. By 30 June 2023, EU MSs are to submit a draft update, with the final update to be delivered by 30 June 2024.[79] This represents a (short) window of opportunity to enhance and harmonise the NECP process at the Penta level. Risks of inaction: supply deficits, stranded assets, inefficient strategic decisions implying higher costs for the final consumers	
Solution	A **joint scenario analysis** as part of the NECP process ensures a coherent picture across countries, integrating: - Harmonised framework assumptions (CAPEX data, energy carrier prices, CO2 price, energy imports, EU target achievement etc.) - National assumptions (e.g. on the evolution of power demand, electrification targets) - National strategies and objectives (e.g. on H2 production/imports)	
Implementation	The process may take several forms: - Agree on a **common set of assumptions** (each country reports national assumptions, some requiring harmonization, e.g. CAPEX, and a common set of hypotheses for the non-Penta countries, e.g. based on a TYNDP scenario) that are considered individually by all Penta members in their preparation of NECPs - A **joint scenario development** exercise, implying the joint development of a common scenario philosophy (regarding the role of certain technologies and energy carriers) which appears then in each NECP	

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[77] Figure based on evolutions observed on a selection of national scenarios (Austria and Luxembourg data not available).

[78] Cf. Chapter 2 of the EU Governance Regulation 2018/1999.

[79] The next full NECP is to be prepared by 1 January 2029, cf. Art. 3 of the EU Governance Regulation 2018/1999.

	- A **joint modelling exercise**, making use of the same modelling environment and implying the generation of a common scenario results dataset (to be integrated into the NECP or as some kind of benchmark process for the NECPs), which provides detailed information about the future siting of energy production/conversion/storage and transmission assets.
Advantages/benefits	- Reveal potential caveats in the existing national scenarios - Draw a (quantifiable) joint vision - Coordinated, cost-efficient siting of RES and electrolyser plants across the entire Penta region - Trigger/enhance coordination between national ministries - Agree on the role of direct/indirect electrification => positive impacts on national infrastructure build-out (e.g., w.r.t. EV charging infrastructure, assuming all Penta countries agree on EVs as the main technology for private passenger road transport)
Barriers/limitations	- Transaction costs/required effort: exercise may involve not only ministries, but possibly also other stakeholders (e.g. TSOs) - Disregards the vision/assumptions from other major European countries
Link to other actions	- Coordination should be sought with the joint/harmonised network development planning approach, cf. Planning.2

7.2.14 Planning.2 - Penta network planning initiative / Joint Penta network development plan

Topic: planning	**Planning.2**	**Penta network planning initiative / Joint Penta network development plan**	
Challenges/risks	- National power transmission networks are to be strongly reinforced to cope with rising power demand and supply volumes.[80] In addition, trans-European transit power flows are expected to increase. Finally, network ageing requires a significant effort in network renewal. Studies show that **transmission networks must be reinforced** by up to 60% by 2050, which requires massive investments. - **Network development plans** (NDPs) are a key element in the energy system transition to ensure that the required grid infrastructure will become available in time; yet, for the time being TSOs develop their NDPs quite independently from their Penta peers o All Penta countries prepare their individual NDPs independently from neighbouring countries, with varying frequency and timeline o Only 2 out of 3 NDPs (at the EU level) consider the NECPs o In most countries, there is at least some alignment between TSOs and DSOs in the preparation of NDPs		

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[80] These reinforcement needs are notably driven by over-proportional commissioning of vRES capacities (due to their lower load factors in comparison to conventional technologies), and the fact the location of RES potentials differs from the location of existing thermal power plants.

	o In none of the countries the electricity NDP is covers jointly electricity, gas and/or hydrogen - This leads to **electricity-centred NDPs** that are little aligned with the national NECP (or underlying objectives) nor with NDPs from neighbouring countries; such a lack in harmonisation may imply sub-optimal investment decisions, stranded assets, potential grid bottlenecks
Solution	- Three options could be envisioned at the Penta level: o An adaptation and **stronger alignment** of the NDP preparation process across Penta countries o The preparation of a **joint Penta network development plan** o Penta to push for an **enhanced TYNDP preparation process**
Implementation	- Adaptation and **stronger alignment of the NDP preparation process** across Penta countries o Apply a 2-year frequency in all countries[81], potentially with harmonised scheduling/timeline and harmonised time horizon (20 years or 2050) o Harmonise information about expected import/export balances with other Penta countries, potentially even temporally disaggregated power exchange profiles o Exchange information about major energy imports, their type (energy carrier, pipeline vs liquefied) and expectations about source countries o Ideally, coverage of gas, electricity and hydrogen (preferably, even including storage and LNG and the link to district heating networks and CC(U)S infrastructure) o Involve stakeholders along the entire energy value chain (generation, transmission, storage, conversion, distribution, consumption), potentially test certain assumptions by means of scenarios/sensitivities o Alignment with national/regional[82]/EU objectives and latest national NECPs - Development of a **Joint Penta NDP** o Joint definition of scenarios and input data (incl. major national assumptions, particular w.r.t. demand evolution and selected supply technologies) ▪ Integrate the visions from a large range of national and regional stakeholders o Apply a collaborative modelling environment (or analysis to be performed by an external consultant), ▪ Covering electricity, gas and hydrogen ▪ Covering all Penta countries plus major neighbours (or the entire EU, in a more aggregated way)

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[81] A 2-year frequency is recommended by ACER (2021): Opinion No 05/2021 of the European Union Agency for the Cooperation of Energy Regulators; https://www.acer.europa.eu/electricity/infrastructure/network-development/consistency-national-and-eu-wide-network-development-plans

[82] This could include some of the objectives suggested in the present document at the level of Penta, or from other regional country clusters, e.g. NSEC.

	▪ Preferably with a sub-national granularity (e.g., NUTS1) ▪ Cover various infrastructure elements (cross-border interconnections, storage) and determine their cost-optimal deployment and localization - Penta to push for an **enhanced TYNDP preparation process** o Go for multi-energy assessment (joint ENTSO-E/ENTSOG analysis, not only w.r.t. scenario design but for the entire analysis, incl. repurposing) - For further information, see also Section 3.4 of the assistance report to the Impact Assessment of the Decarbonised Gas Package (Artelys, Trinomics, Fraunhofer IEE, JRC, 2021))
Advantages/benefits	- Enhanced coordination between TSOs on the NDP or even a joint NDP would raise awareness along TSOs and involved stakeholders about the challenges tackled in other Penta countries - The effort for a joint Penta NDP would directly incentivise an exchange on best practices and enhance the quality of individual NDPs - Improving the TYNDP process has benefits beyond the scope of Penta
Barriers/limitations	- Network planning is a quite complex and time-consuming task; requiring enhanced coordination makes the process lengthier, costlier and potentially less capable to easily adapt to new framework conditions - Enhanced streamlining/coordination of the NDP process implies significant additional transaction costs for all involved entities - A unique joint Penta NDP might apply a lower granularity than national NDPs; difficulty to ensure coherence - Requirements on TYNDP process might interfere to a certain extent with the provisions of the new TEN-E regulation, which requires EU MSs to work together (in the case of offshore network development plans)
Link to other actions	- Network planning should be aligned with the coordinated NECP process (Planning.1) - Network planning should apply state-of-the-art modelling approaches and best practices (cf. Planning.3) and coordinate with distribution grid planning (Grids.2)

7.2.15 Planning.3 - Promote best practice recommendations for future system modelling

Topic: planning	**Planning.3**	**Promote best practice recommendations for all future energy system/network modelling activities**	
Challenges/risks	The decarbonisation of energy systems requires an enhanced integration: - The enhanced coupling of energy sectors (power, heat, transport etc.) and energy carriers (power, hydrogen, gas…) and - Geographical integration o Vertical integration: interactions of local, national and regional systems have to be taken into account and leveraged o Horizontal integration: national systems are to be increasingly connected in order to facilitate resource allocation and ensure system stability		

	Identifying the optimal trade-off between different technology options in an **increasingly interconnected and complex energy system** represents a major challenge for all decision makers (politics, grid operators, investors). Conventional isolated modelling approaches (e.g. power-only or gas-only) may fall short at taking these interactions into account and build cost-efficient, robust systems.
Solution	Penta to promote energy system design via common and integrated best-practice modelling approaches.
Implementation	Penta shall encourage integrated modelling approaches for system/network design activities via continuous benchmarking and coordination between members. Common modelling recommendations may be based on the following guidelines: **Modelling scope and assumptions** - Modelling scope conditions the potential endogenous choices that can be achieved via calculations; set the scope as large as necessary, but as tight as possible - The optimisation of capacity expansion to dimension future energy supply systems allows to derive cost-optimal solutions; yet, it may require the consideration of several weather years (ideally incorporating climate change) and the establishment of specific constraints to ensure a realistic model behaviour. A complete library of likely low-carbon technologies and the most recent techno-economic assumptions facilitate the preparation of robust and meaningful results. - Multi-energy modelling reveals synergies and identifies avoidable infrastructure needs; it is essential to assess optimal trade-offs between different energy carriers, while factoring in the enhanced interactions between different economic sectors. - End-use level modelling allows for specific end-use flexibility behaviour representation (space heating, electric vehicles…) and may facilitate the endogenous optimisation of the energy carrier mix (based on end-uses respective volumes and dynamics) - Resource availability and exogenous assumptions (e.g. political choices like specific technology support or phase-out) have to be carefully integrated as they condition the available choices. - Sensitivities are a powerful means to reveal system dynamics and identify tipping points between system equilibria. - Pathway modelling, covering entire trajectories between a historic reference year and a target year (e.g., 2050) properly reflect investment dynamics, avoid technology lock-ins and stranded assets and ensure coherence between short term decisions and long-term targets. **Geographical granularity** - A fair representation of cross-border exchanges is essential to reflect cooperation opportunities regarding resource availability (production, storage…) and flexibility provision - In increasingly interconnected regional systems, strategies in more distant areas as well as reliance on energy imports may have tangible impacts on the focus area - For larger territories, a sub-national granularity is relevant as internal infrastructure will be a condition to the national strategy success **Time granularity** - System dynamics are better represented in year-long hourly modelling environments, which facilitates leveraging intra-day demand-side flexibility, preferably modelling the entire pathway between today and the target year (e.g. 2050)

	- Results' robustness has to be ensured via testing several multiple weather years, in particular when it comes to adequacy assessments and power system dimensioning
Advantages/benefits	- Common modelling practices facilitate comparison and integration of model results - Increase the value of modelling exercises performed and facilitate the design of sound strategies
Barriers/limitations	- More complex modelling approaches require a more significant amount of effort and make the modelling process more lengthy, less agile (implying the risk that results are already outdated once determined)
Link to other actions	- The integration of recommendations in national transmission systems, see Planning.2 - Encourage coordinated NECP preparation and ensure consistency via joint modelling, cf. Planning.1

7.2.16 DSF.1 - Penta smart demand initiative

Topic: DSF	**DSF.1**	**Penta smart demand initiative**
Challenges/risks	The (direct and indirect) **electrification** of the economy will significantly increase power demand, by 60% to 90%[83] in the Penta region, by 2050. If the demand from new (and existing) electricity end consumers remains **inflexible**, a relevant flexibility potential remains untapped, but it even further increases flexibility needs (from alternative sources) and systems costs. Different initiatives were taken at the national and EU level, yet a large share of the DSF potential still (in particular from small and decentralised consumers) remains untapped. Participation is dominated by industrial and commercial loads with residential and local flexibility still lagging behind. Transposition and implementation of the 2019 Electricity Market Directive lags behind schedule.[84]	
Solution	**Demand-side flexibility (DSF)**, as the flexible and smart operation of electricity end uses is one major source of flexibility (next to transmission grids, storage and flexible power generation, cf. Grids.1, Grids.2 and Storage.1). Penta countries could become the front runners in this domain, by committing to DSF, streamlining efforts, making use of existing (optional) EU instruments – and by learning from each other (e.g., following the example of FR featuring a dedicated Demand Response product in the national resource adequacy mechanism or the newly designed capacity mechanism in BE).	
Implementation	- Different dimensions and degrees of ambition o General	

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[83] Figure based on evolutions observed on a selection of national scenarios (Austria and Luxembourg data not available).

[84] smarten (2022): The implementation of the electricity market design to drive demand-side flexibility; https://smarten.eu/wp-content/uploads/2022/03/The_implementation_of_the_Electricity_Market_Design_2022_DIGITAL.pdf

- Sharing of information/best-practices within Penta and across the EU
    - FR/BE/PL: integration of DSF in capacity markets
    - IE: Integration of DSF in ancillary services
- Joint strategy on the publication (obligation) of market-related data with high temporal granularity, to facilitate the emergence of new market actors (such as aggregators)
- Harmonised/coordinated implementation of the 2019 electricity market directive
    - Smart meter roll-out (Art. 19, 21): DE, BE lag behind[85]
    - Dynamic price contracts and grid tariffs, right to conclude an aggregation contract (Art. 11, 13, 15) to pass savings on to the consumers
    - Adapt reserve markets for non-discriminatory market access (Art. 15, 17)
- Review of network codes to remove barriers for DSF; development of a joint position for the establishment of a network code on demand-side/distributed flexibility[86],[87]
- Adapted design of existing flexibility markets (product design, gate closure times etc.)
- Inclusion of DSF in resource adequacy mechanisms[88]

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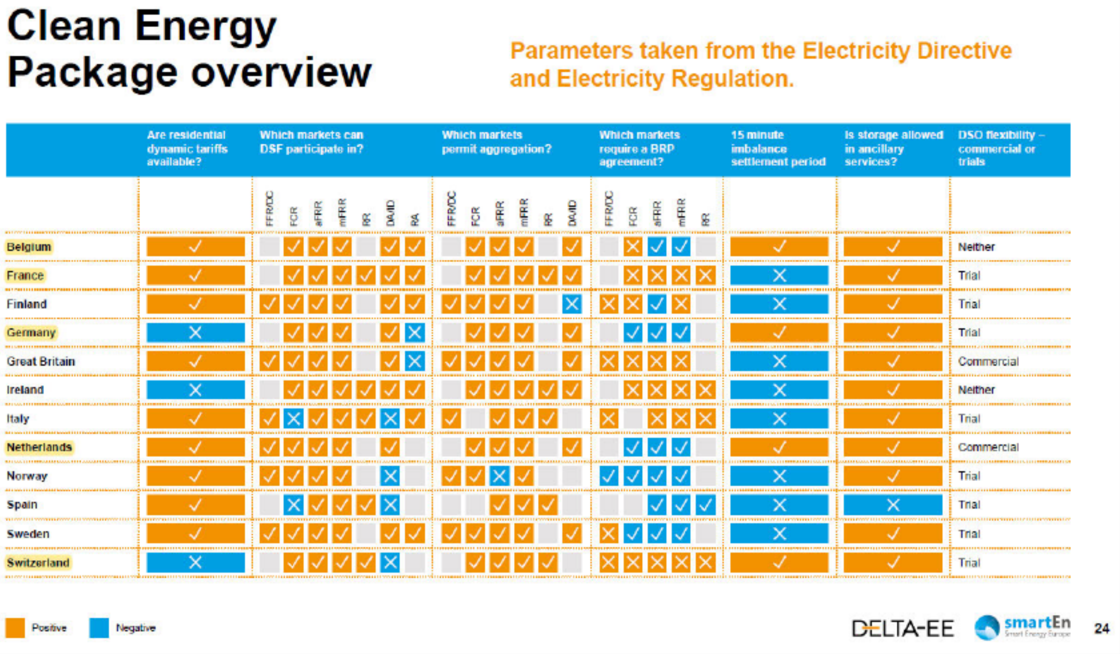
[85] Tractebel Impact (2019): Benchmarking smart metering deployment in the EU-28; https://energy.ec.europa.eu/benchmarking-smart-metering-deployment-eu-28_en

[86] CEDEC, E.DSO, ENTSO-E, Eurelectric, GEODE (2021): Roadmap on the Evolution of the Regulatory Framework for Distributed Flexibility; http://www.cedec.com/files/default/210728_TSO-DSO_Roadmap_on_Distributed_Flexibility.pdf

[87] smarten (2021): A Network Code for Demand-Side Flexibility; https://smarten.eu/position-paper-a-network-code-for-demand-side-flexibility/

[88] smarten (2022): The smarten map – Resource Adequacy Mechanisms; https://smarten.eu/wp-content/uploads/2022/01/the_smarten_map_2021_DIGITAL_final.pdf



Clean Energy Package overview

Parameters taken from the Electricity Directive and Electricity Regulation.

	Are residential dynamic tariffs available?	Which markets can DSF participate in?							Which markets permit aggregation?						Which markets require a BRP agreement?					15 minute imbalance settlement period	Is storage allowed in ancillary services?	DSO flexibility – commercial or trials
		FFR/DC	FCR	aFRR	mFRR	RR	DA/ID	RA	FFR/DC	FCR	aFRR	mFRR	RR	DA/ID	FFR/DC	FCR	aFRR	mFRR	RR			
Belgium	🟧✓		🟧✓	🟧✓	🟧✓		🟧✓	🟧✓		🟧✓	🟧✓	🟧✓		🟧✓		🟧✗	🟦✓	🟦✓		🟧✓	🟧✓	Neither
France	🟧✓		🟧✓	🟧✓	🟧✓	🟧✓	🟧✓	🟧✓		🟧✓	🟧✓	🟧✓	🟧✓	🟧✓		🟧✗	🟧✗	🟧✗	🟧✗	🟦✗	🟧✓	Trial
Finland	🟧✓	🟧✓	🟧✓	🟧✓	🟧✓		🟧✓	🟧✓	🟧✓	🟧✓	🟧✓	🟧✓		🟦✗	🟧✗	🟧✗	🟦✓	🟧✗		🟦✗	🟧✓	Trial
Germany	🟦✗		🟧✓	🟧✓	🟧✓		🟧✓	🟦✗		🟧✓	🟧✓	🟧✓		🟧✓		🟦✓	🟦✓	🟦✓		🟧✓	🟧✓	Trial
Great Britain	🟧✓	🟧✓	🟧✓	🟧✓	🟧✓		🟧✓	🟦✗	🟧✓	🟧✓	🟧✓	🟧✓		🟧✓	🟧✗	🟧✗	🟧✗	🟧✗		🟦✗	🟧✓	Commercial
Ireland	🟦✗		🟧✓	🟧✓	🟧✓	🟧✓	🟧✓	🟧✓		🟧✓	🟧✓	🟧✓	🟧✓	🟧✓		🟧✗	🟧✗	🟧✗	🟧✗	🟦✗	🟧✓	Neither
Italy	🟧✓	🟧✓	🟦✗	🟧✓	🟧✓	🟧✓	🟦✗	🟧✓	🟧✓		🟧✓	🟧✓	🟧✓		🟧✗		🟧✗	🟧✗	🟧✗	🟦✗	🟧✓	Trial
Netherlands	🟧✓	🟧✓	🟧✓	🟧✓	🟧✓		🟧✓			🟧✓	🟧✓	🟧✓		🟧✓		🟦✓	🟦✓	🟦✓		🟧✓	🟧✓	Commercial
Norway	🟧✓	🟧✓	🟧✓	🟧✓	🟧✓		🟦✗		🟧✓	🟧✓	🟦✗	🟧✓			🟦✓	🟦✓	🟦✓	🟦✓		🟦✗	🟧✓	Trial
Spain	🟧✓		🟦✗	🟧✓	🟧✓	🟧✓	🟦✗				🟧✓	🟧✓	🟧✓				🟦✓	🟦✓	🟦✓	🟦✗	🟦✗	Trial
Sweden	🟧✓	🟧✓	🟧✓	🟧✓	🟧✓		🟧✓	🟧✓	🟧✓	🟧✓	🟧✓	🟧✓		🟧✓	🟧✗	🟦✓	🟦✓	🟦✓		🟦✗	🟧✓	Trial
Switzerland	🟦✗		🟧✓	🟧✓	🟧✓	🟧✓	🟦✗			🟧✓	🟧✓	🟧✓	🟧✓		🟧✗	🟧✗	🟧✗	🟧✗	🟧✗	🟧✓	🟧✓	Trial

🟧 Positive 🟦 Negative

[89]

- Electric vehicles
    - Joint commitment to promote the deployment of bi-directional charging infrastructure (in particular for charging infrastructure 'at home' and 'at work', featuring sufficiently parking times)
    - Enhanced joint research on battery degradation from V2G
    - (Coordinated support of the CCS or CHAdeMO charging standard)
- Buildings

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[89] Delta-EE, smartEn (2021): European Market Monitor 2021 for demand side flexibility; https://smarten.eu/wp-content/uploads/2022/02/EU_Market_Monitor_2021_PUBLIC_ONLINE.pdf

	▪ Joint commitment to implement the Smart Readiness Indicator[90] (so far only tested in Penta countries AT and FR) ○ See also (Trinomics, Artelys, 2023) for further recommendations
Advantages/benefits	- Pushing for a rapid transposition and implementation of the 2019 Electricity Market Directive may have positive side effects (and protect Penta countries against infringement procedures)
Barriers/limitations	- The promotion of EVs thwarts to a certain extent the required transition in the transport sector away from individual car passenger transport towards public transport, car sharing etc. - "No Member State has transposed provisions [from the Electricity Market Directive] related to DSOs' flexibility procurement fully. Member States would rather wait for the network code on Demand-Side flexibility, which is currently under development and may bring further rules on DSOs' flexibility procurement. Therefore, at this point, opting for a detailed national framework for demand-side flexibility, aggregation and storage may lead to situations where the Member States introduce national provisions that might end up being in contrast with the upcoming network code and thus require to be changed later."[91] - A coordinated implementation of the Electricity Market Directive entails significant coordination efforts among Penta countries and risks delaying the implementation process - Electrolyser flexibility only available if electrolysers are installed in the Penta countries => depends on Hydrogen strategy
Link to other actions	- Electrolyser flexibility depends on the availability and location of electrolysers (cf. Hydrogen.1) and the availability of hydrogen storage capacities (cf. Storage.1)

7.2.17 Storage.1 - Joint Penta storage deployment initiative

Topic: storage	**Storage.1**	**Joint Penta storage deployment initiative**	
Challenges/risks	**Storage technologies** will be one of the main pillars to ensure continuously the supply/demand equilibria in the future coupled energy systems. - **Power:** RES-intensive power systems will require flexibility provision on all timescales (sub-hourly, daily, weekly, seasonal). Stationary power storage capacities need to be reinforced (30 GW of batteries in 2030 and 70 GW in 2050[92], in the Penta region), complemented		

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[90] This indicator allows for rating the smart readiness of buildings, i.e., the capability of buildings (or building units) to adapt their operation to the needs of the occupant, also optimizing energy efficiency and overall performance, and to adapt their operation in reaction to signals from the grid (energy flexibility).

[91] FSR (2022): Distributed resources and flexibility; https://fsr.eui.eu/distributed-resources-and-flexibility/

[92] Based on TYNDP 2022, Global Ambition scenario

	by V2G and hydro storage potentials (+7 GW by 2050) which are not evenly distributed across Penta countries, though (concentration in FR, DE, CH, AT). - **Heat:** Heat systems (decentralised heat pumps, district heating networks) are to be increasingly electrified. Thermal inertia of buildings but in particular dedicated heat storage facilitates may act as a buffer between low-carbon/cost power generation and periods of higher heat demand, adding flexibility to the power grid and remove grid congestions. Yet, a common vision lacks how much heat storage capacities are to become operational in the medium-/long-term perspective. - **Hydrogen:** Massive hydrogen volumes are to be imported, produced and consumed in the Penta area. Notably, hydrogen imports and domestic electrolyser operation are expected to fluctuate at the seasonal scale, while bulk of demand is expected rather flat (transports, industry…). On top of direct demand, thermosensitive power-dedicated H2 demand could take place if P2G2P loops are implemented. In that case, H2 demand dynamics would oppose to power-based hydrogen generation dynamics. Hydrogen storage will be a key prerequisite to make the hydrogen economy materialize. In Germany alone, hydrogen storage capacities are estimated to total 47 to 73 TWh by 2050[93]. Additional assessments are necessary to determine Penta-wide objectives, in coordination with hydrogen transmission infrastructure projects. Yet, H2 storage potentials are available in selected Penta countries only (DE, NL, FR).
Solution	A **joint storage strategy** can help to ensure a rapid deployment of the available storage potentials, allowing for best practice sharing, the initiation of joint pilot projects and the establishment to jointly finance, commission, connect and exploit these storage facilities.
Implementation	The joint storage strategy may be composed of different elements: - Identify common storage needs at the Penta level, based on assessments taking into account sector-coupling and considering a high temporal granularity to identify the benefits of storage at all timescales - Promote cooperation within Penta in order to leverage storage potentials where available (potentially by making use of the European Cross-border Cost Allocation mechanisms set up by ACER[94]) - Agree on and enforce common rules for asset operation at the Penta level, e.g. commitments by hosting countries to ensure continuous operational conditions, consistent interconnector development and operations that foster storage resource sharing - Joint R&D efforts or pilot projects on hydrogen storage
Advantages/benefits	- Increase Penta's feasibility to exploit domestic energy resources (RES, H2 etc.), thereby decreasing import dependency

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[93] Based on BMWi's TN-Strom and TN-H2 scenarios. Bundesministerium für Wirtschaft und Energie (BMWi) (2022), Langfristszenarien für die Transformation des Energiesystems in Deutschland

[94] Regulation (EU) No 347/2013 of the European Parliament and of the Council of 17 April 2013 on guidelines for trans-European energy infrastructure and repealing Decision No 1364/2006/EC and amending Regulations (EC) No 713/2009, (EC) No 714/2009 and (EC) No 715/2009 Text with EEA relevance, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32013R0347

	- Enhance strategic alliance via increased interdependency of Penta energy systems and interest alignment - Reduce overall system costs as storage enables efficient resource allocation
Barriers/limitations	- May interfere with the EU/TYNDP PCI/IPCEI process
Link to other actions	- Coordinated system planning within Penta: Planning.1 - Storage deployment has to be coordinated with demand-side flexibility developments, DSF.1 - Hydrogen storage needs have to be determined jointly with supply streams, demand volumes and dynamics, transmission infrastructure projects, namely a joint Hydrogen strategy: Hydrogen.1

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