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Deployment Scenarios for Low Carbon Energy Technologies

Deliverable D4.7 for the Low Carbon Energy Observatory (LCEO)

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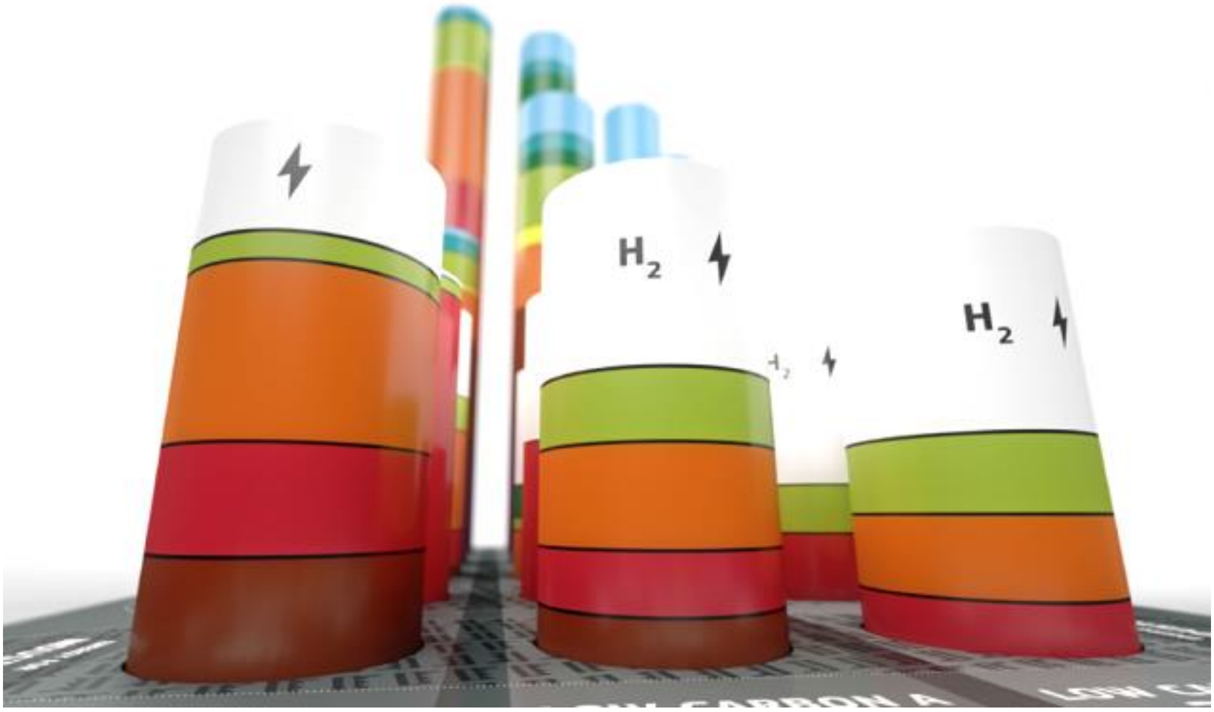

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Foreword about the Low Carbon Energy Observatory

The LCEO is an Administrative Arrangement being executed by JRC for RTD, to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies are covered?

- Wind Energy
- Photovoltaics
- Solar Thermal Electricity
- Solar Thermal Heating and Cooling
- Ocean Energy
- Geothermal Energy
- Hydropower
- Heat and Power from Biomass
- Carbon Capture, Utilisation and Storage
- Sustainable advanced biofuels
- Battery Storage
- Advanced Alternative Fuels

In addition, the LCEO monitors future emerging concepts relevant to these technologies.

How is the analysis done?

JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main deliverables?

The project produces the following generic reports:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Report on Synergies for Clean Energy Technologies
- Annual Report on Future and Emerging Technologies (information is also systematically updated and disseminated on the online FET Database).

Techno-economic modelling results are also made available via dedicated review reports of global energy scenarios and of EU deployment scenarios.

What's the timeline?

The LCEO produces its main reports on a two-year cycle. The first set was published in 2016 and the second will be available in 2018. A final set will be released in spring 2020.

How to access the deliverables

Commission staff can access all reports on the Connected LCEO page. These are restricted to internal distribution as they may contain confidential information and/or assessments intended for in-house use only. Redacted versions will also be distributed publicly on the SETIS website.

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Executive summary

This report provides an outlook for deployment of a set of low carbon energy technologies, as well as background on how JRC-EU-TIMES baseline and decarbonisation scenarios are derived. The scenarios and sensitivities have been co-created together with the client. The results help inform decision makers on the technology choices through which the EU can meet its climate and energy goals under different global energy scenarios. The report also provides background for the technology specific results in the LCEO technology and market reports.

Key conclusions

- In a diversified world that decarbonises by using all technology options, including CCS and nuclear power
    - The level of nuclear, coal and gas remains similar to baseline scenarios
    - Oil consumption is reduced by 60%, twice the reduction seen in baseline scenarios and part of the oil is replaced by hydrogen and electrofuel from variable renewable sources.
    - Almost 60% of the total CO_2 is stored or used, mostly captured from power production or fossil based hydrogen or collected as a by-product from the production of 2nd generation biofuels.
    - Additional CO_2 is also directly captured from the air, especially under the assumption of a high technology learning rate.
    - Permanent storage of CO_2 occurs in the countries where underground storage of CO_2 has not been restricted yet.
    - Such transformations would require a rapid scale-up of CCS technologies.
- In a pro renewables world that decarbonises with mainly renewable resource
    - Remarkable amounts of solar and wind will have to be installed in the absence of nuclear and CCS.
    - 84% of the final energy comes from renewable sources with the transport sector being almost entirely renewable.
    - Biomass and hydro are used up to their technical, sustainable potential. Wind, solar, geothermal and ocean are used up to the economic optimum.
    - Power-to-Liquid (electrofuel) complements biofuels in sectors with no easy electric alternative like aviation.
    - The CO_2 that is required to produce for example kerosene is collected mainly as a by-product from 2nd generation biofuel facilities.
    - Biomass is in most cases equipped with CCS, whether it is for power, heat or biofuels.
    - Without option to permanently store CO_2, Direct Air Capture does not play a role.

Quick guide

After the introduction, chapter 2 to 5 provide more background on the assumptions from the modelling work. Chapter 6 provides results that improve the understanding of the energy system context. Chapter 7 provides an outlook for the low carbon energy technologies covered within the AA.

1 Introduction

In this report, scenarios are presented for the deployment of low carbon energy technologies. These scenarios and sensitivities have been developed for the LCEO AA following a workshop that took place in September 2017. These scenarios help inform decision makers on the technology choices through which the EU can meet its climate and energy goals under different global energy scenarios, thereby supporting the accelerated development and deployment of low carbon technologies. The report also provides more background for the results produced in the context of the AA and used for the technology and market reports of the technologies in focus.

At the 21st Conference of Parties in Paris (COP21) in 2015, the decision was taken by 195 countries to limit global temperature increase to well below 2 ^{o}C above pre-industrial levels by the end of this century, while aiming at 1.5 ^{o}C [1]. The EU, having agreed on its post-2020 framework of climate and energy policy [2] [3], committed to a 40 % domestic greenhouse gas (GHG) emission reduction by 2030 compared to 1990 as the combined contribution of its Member States to global climate change mitigation goals [4]. In line with the longer term objective towards a low carbon economy, this EU target is part of the broader strategy for a secure, sustainable and competitive Energy Union via five mutually supportive and closely related dimensions: (a) energy security, solidarity and trust, (b) fully integrated European energy market, (c) energy efficiency as a contribution to the moderation of energy demand, (d) decarbonisation of the economy and (e) research, innovation and competitiveness [5]. Within the Energy Union strategy and the Clean Energy For All Europeans legislative package, the EU declares its ambition to achieve "[…] *global leadership in renewable energies*" [6] and become the "[...] *global hub for developing the next generation of technically advanced and competitive renewable energies*" [5].

Technological innovation is key for the EU to accelerate the transition to a low carbon economy in a cost effective manner while becoming the world leader in renewable energy. Building on the experience and results of the Strategic Energy Technology Plan (SET Plan) [7], a new integrated SET Plan is seen as the main vehicle to steer research and innovation required for the transformation of the European energy system and support the competitiveness of the European industry, by ultimately leading to new or improved technologies at lower costs [8].

As such, technology progress is a dynamic process that occurs in a complex environment and at a global scale. The prioritisation of technologies and the required actions by the EU to meet its goals can therefore benefit from an analysis that captures global aspects of technology competitiveness. The influence of global developments on EU technology choices is captured through external **global energy deployment scenarios and their effect on investment costs** based on learning effects.

Answering these prioritisation questions requires an energy systems-wide perspective as also indicated by the public consultation in support of the Energy Technology and Innovation Communication [8]. The energy systems approach ensures that dynamics of the interlinked dimensions of the Energy Union strategy are captured. In extension, an energy systems cost-optimisation framework also caters for the requirement to achieve climate and energy goals in a cost effective manner. For this purpose, **scenarios from the European energy systems model JRC-EU-TIMES** are used [9]. JRC-EU-TIMES is designed to analyse the role of energy technologies and their innovation needs for meeting European policy targets related to energy and climate change. The overarching storylines of the global energy scenarios are translated to scenario parameters for the EU and the estimated techno-economic trajectories of low carbon energy technologies are used as model inputs by JRC-EU-TIMES. The model provides estimates on the cost effective technology pathways for the EU to meet its climate and energy goals under different global energy scenarios.

2 Global energy scenarios and technology costs

Identifying a plausible global deployment range of low carbon energy technologies becomes relevant as the more experience is gained through the deployment of a technology at a global scale the more its capital investment costs may decrease. This may come as a result of learning in technical innovation, changes in production processes, economies of scale and so forth, which in turn may be driven by other factors such as Research and Development (R&D) investments. It is empirically shown that investment costs may decrease by a constant factor (learning rate) with every doubling of installed capacity [10]. In the context of the Energy Union strategy, the prioritisation or research and innovation needs in order to accelerate the deployment of low carbon energy technology and deliver them at low costs may differ to the extent that global developments influence capital investments.

Future growth trajectories, however, are not uniquely defined. A review of global energy scenarios conducted by the Knowledge for the Energy Union Unit of the JRC showed that long term technology pathways may vary significantly not only on size but also on the technology portfolio [11]. The projected deployment trajectories of renewable energy supply (RES) technologies for the electricity sector (RES-E) may differ almost by a factor 6 in 2050 (**Figure 1**, right).

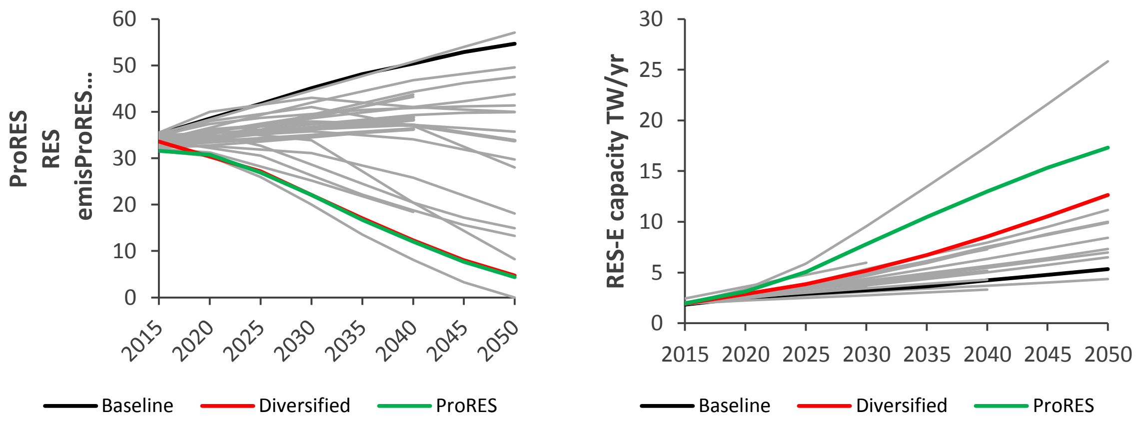

Figure 1. Long term CO_2 emissions (left) and RES-E capacity (right) in global energy scenarios of electrification in final demand and RES in gross electricity

Higher deployment levels of low carbon technologies were found in scenarios that follow a decarbonisation paradigm, which aim to meet longer term climate goals. Scenarios that apply only marked-based incentives or prioritise energy security, project lower growth for low carbon energy technologies and do not meet climate goals. Another explanation lies in the diversity of the technology portfolio assumed in each study. Even in scenarios with comparable emission levels, a trade-off is observed between deployment levels of RES-E technologies and Carbon Capture and Storage (CCS). Several other reasons exist that may explain different growth projections such as the modelling paradigm followed (simulation vs optimisation), technology cost assumptions, development (e.g. role of energy efficiency) or structure (e.g. electrification) of energy demand. These factors ultimately shape the solution space in which models estimate future growth trajectories of technologies.

Table 1 Summary indicator differentiation in the selected scenarios

	RES-E deployment	Technology costs	Global emissions 2050[1]	Electrification	Technology diversification	Global energy demand[2]	EU leadership in RES 2050[3]
Baseline	Low	High	+ 77 %	Low	High	n.a.	In all RES except geothermal
Diversified	Moderate	Moderate	- 80 %	Moderate	High	- 38 %	In all RES except solar and geothermal
ProRES	High	Low	- 80 %	High	Low	- 54 %	In all RES except solar, geothermal and ocean

[1] Compared to 1990

[2] Compared to the "Baseline" projections in 2050

[3] EU leadership is reached in all RES by2050, expressed as RES-E share in EU, compared to China and USA. In the ProRES scenario, OECD Europe is compared North America and China (see Annex)

2.1 Global scenario definitions

In this analysis, scenarios that follow the decarbonisation paradigm are selected and are sufficiently different to cover a plausible range of worldwide development of low carbon energy technologies to 2050: "**Baseline**", "**Diversified**" portfolio and "**ProRES**". The "Baseline" scenario is used as a reference. The scenario description is as follows:

Baseline scenario

- The "Baseline" scenario is used to cover the lower end of global RES-E deployment. It is based on **the "6DS" scenario of the Energy Technology Perspectives** published by the International Energy Agency in 2016 [15].
- It represents a "business as usual" world in which no additional efforts are taken on stabilising the atmospheric concentration of GHGs. By 2050, primary energy consumption reaches about 940 EJ, renewable energy supplies about 30 % of global electricity demand and emissions climb to 55 $GtCO_2$.

While adequately different in RES-E deployment levels, the "Diversified" portfolio and the "ProRES" scenarios (decarbonisation scenarios) achieve similar emission reduction globally (about 80 % by 2050 compared to 1990;**Figure 1**, left), have different technology portfolio with respect to fossil fuels, nuclear energy and CCS, and are amongst those scenarios with the highest reduction in primary energy demand (compared to the "Baseline" projections in 2050).

Diversified scenario (Div1)

- The "Diversified" portfolio scenario is derived from **the "B2DS" scenario of the International Energy Agency's 2017 Energy Technology Perspectives** [16] and is used as representative for the mid-range deployment of RES-E found in literature.
- To achieve rapid decarbonisation in line with international policy goals, all known supply, efficiency and mitigation options are available and pushed to their practical limits. Fossil fuels and nuclear energy participate in the technology mix, and CCS is a key option to realise emission reduction goals. Primary energy consumption is comparable to 2015 levels (about 580 EJ), the share of renewable electricity in the global supply mix is 74 % while emissions decline to about 4.7 $GtCO_2$ by 2050.

At a global level, the main difference between the two decarbonisation scenarios is that by 2050 electricity in "ProRES" is almost exclusively produced by renewables (Figure 2. , left). Electrification of final demand increases earlier in "ProRES" compared to "Diversified" (Figure 2. , left) but remains comparable up until 2050 when the difference becomes pronounced (higher than 10 % p.p.). Finally, in "ProRES", slightly less than 50 % of final energy demand is met by electricity. The projections of electrification and RES-E share of the EU are comparable with those of at a global level by 2050 (Figure 2.).

ProRES scenario (Res1)

- The "ProRES" scenario results are the most ambitious in terms of capacity additions of RES-E technologies. In this scenario the world moves towards decarbonisation by significantly reducing fossil fuel use, however, in parallel with rapid phase out of nuclear power. CCS does not become commercial and is not an available mitigation option.
- Deep emission reduction is achieved with high deployment of RES, electrification of transport and heat, and high efficiency gains.
- It is based on the **2015 "Energy Revolution" scenario of Greenpeace** [11]. Primary energy consumption is about 430 EJ, renewables supply 93 % of electricity demand and global CO_2 emissions are about 4.5 $GtCO_2$ in 2050.

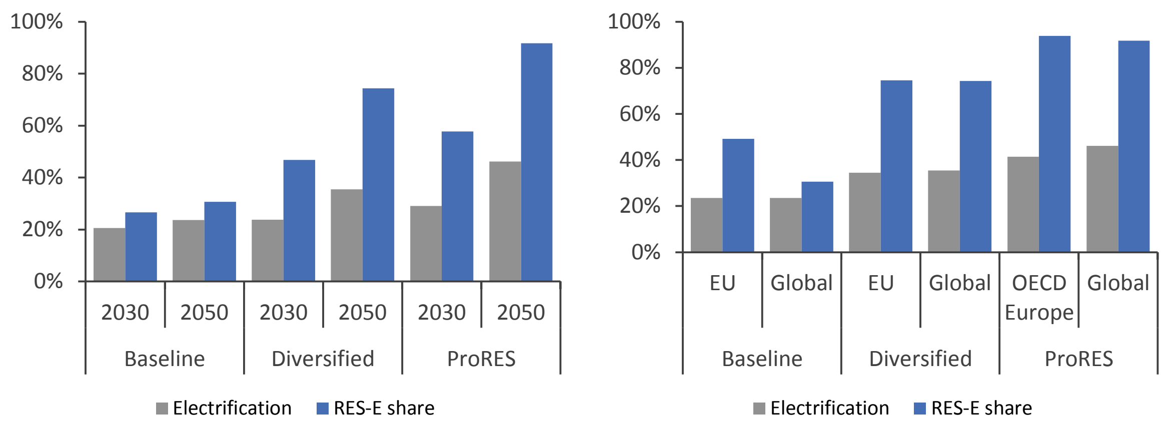

Figure 2. Share of electrification in final demand and RES in gross electricity generation globally over time (left figure) and in the EU compared to the world in 2050 (right figure). EU and Global Electrification and RES converge in the Diversified and ProRES scenarios

2.2 Deriving cost trajectories from learning

Capital investment cost trajectories of individual low carbon energy technologies are derived based on their projected deployed capacity in the "Baseline", "Diversified" and "ProRES" scenario, under the assumptions of high, reference and low technological learning, expressed by varying learning rates. The "ProRES" scenario returns the highest bound of capital investment cost reduction, whilst the "Diversified" portfolio scenario returns more moderate improvements. The "Baseline" scenario is most conservative in terms of reduction of technology costs over time.

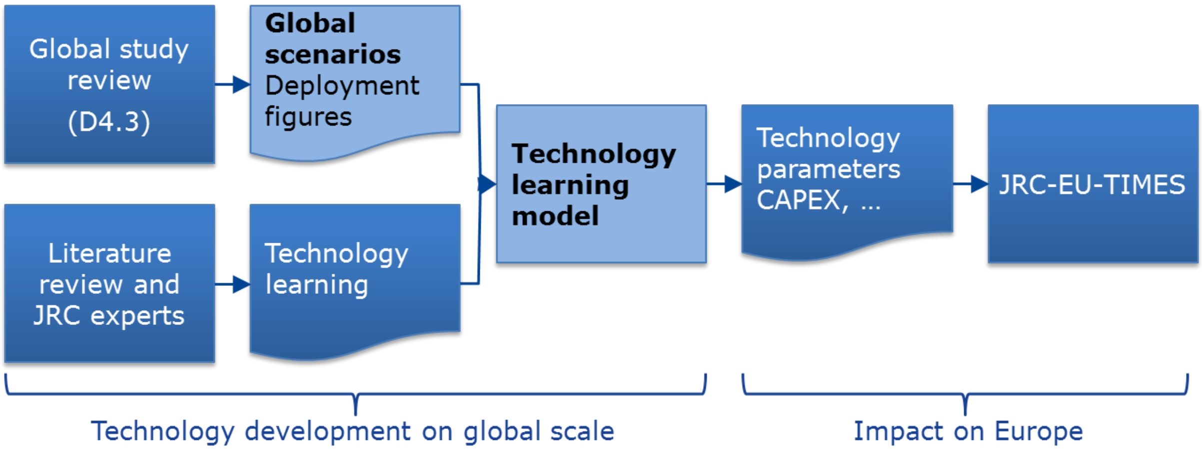

Figure 3. Schematic overview of connecting the Technology Learning model with the energy system model JRC-EU-TIMES

Using the learning rate methodology under global scenario storylines one can yield internally consistent technology cost trajectories [12]. The learning rate method is described by the equation:

$$Cost_t = Cost_0 \cdot \left(\frac{C_t}{C_0}\right)^{\varepsilon}$$

Eq. 1 Cost reduction based on the learning rate method

, where $Cost_t$ is the unit cost of the technology in year t after the cumulative deployment of C_t units, $Cost_o$ is the cost of the unit of production at cumulative deployed capacity C_o at time $t = 0$ and ε is the experience parameter. The learning rate (LR) and the experience parameter are described by the following equation:

$$LR = 1 - 2^{\varepsilon}$$

Eq. 2 The learning rate and the experience parameter

2.3 Scenario-based cost trajectories

The estimated long term cost trajectories of low carbon energy technologies under these scenarios and all related assumptions can be found in the technical report prepared by the JRC [12]. The above explained learning rate method resulted in sensitivities with lower and higher learning rates: Div2_LowLR, Div3_HighLR, Res2_LowLR and Res3_HighLR. For some key technologies, the CAPEX and Levelised Cost Of Electricity (LCOE) are given in Annex 2-7. The LCOE is derived from data that are inputs to JRC-EU-TIMES but is not an input itself. The LCOE does not take into account the total impact on the power system and is for that reason only an indicative cost indicator.

3 EU assumptions in the global context

JRC-EU-TIMES includes exploratory and normative elements. It is exploratory with respect to technology choices but it is normative with respect to the overall EU climate and energy policy goals. This chapter gives an overview of all the assumption that are related to EU policies.

3.1 EU specific assumptions

EU specific assumptions for each scenario are as follows:

All scenarios - general

- We assume a lifetime extension of existing nuclear power plants up to 60 years in the countries without a phase-out policy.
- The scenarios are aligned with following inputs of the Reference Scenario 2016 in the long run, up to 2050:
    - Energy services demand or demand growth
    - Fuel prices
    - Building stock projection
    - The total MS capacities of coal power plants from the Reference Scenario 2016 are used as an upper limit for coal power plants without CCS in JRC-EU-TIMES.
- We introduced restriction to geological storage of CO_2 in line with [26]. Some Member States do not allow CO_2 storage on their territory or part of it due to unsuitability of their geology for CO_2 storage (Finland, Luxembourg and the Brussels Capital Region of Belgium). A few Member States do not allow geological storage of CO_2 (Austria, Croatia, Estonia, Ireland, Latvia, Slovenia) or restrict it offshore (the Netherlands, UK, Sweden), in time (Czech Republic), in quantity (Germany) or for demonstration purposes only (Poland).

All scenarios - 2030

	2030	Ref year
Renewable Energy	>27%	-
Primary Energy	-23% (-30%)	2005 (2030)
CO_2 total	-40%	1990
CO_2 total	-36%	2005
Emissions Trading Scheme (ETS)	-43%	2005
Non-ETS	-30%	2005

- In line with the Clean Energy package proposal from November 2016, there is a minimum reduction of the primary energy consumption (excluding non-energy) of 30% in 2030. The goal of that target is to limit the primary energy consumption to 1320 Mtoe, which is a 30% decrease compared to the same 2030 baseline. The 30% target is equivalent to a reduction of 23%, when compared to the historical energy consumption of 2005.
- As in line with what was agreed at the European Council in October 2014 it has a minimum renewable energy of 27% in 2030 (as a share of final energy consumption).
- These targets (30%EE and 27%RES) were agreed at the time when the new targets (32.5%EE and 32%RES) were not known. The decarbonisation scenarios however have a share of renewable energy and EE that are very close to the targets in place now.
- The collective EU target is to reduce the economy wide greenhouse gases with at least 40% compared to 1990. The 40% target is equivalent to a reduction of 36%, when compared to the historical emissions of 2005.
- There is an EU wide ETS target of -43% emission reductions compared to 2005.
- The proposed emission targets for individual member states to achieve a 30% reduction in GHG emissions by 2030 under the EU's Effort Sharing Regulation (ESR), meaning from non-ETS (Emissions Trading System) sectors. An ESR (non-ETS) target is proposed for 2030: -30% below 2005 levels, comprising ESD and LULUCF.
    - Within JRC-EU-TIMES we have included the MS specific targets from proposal COM 2016/482. This is different from the outputs of the EUCO30 scenario where there is a cost optimal MS effort sharing.
    - ESR CO_2 emission reductions seem to differ from the official numbers in the proposal but this is because we only take CO_2 whereas the official numbers are for all GHG.
    - We assume the linear reduction starts in 2018 with a value of the emissions projection of EUCO30 for 2020 which is lower than the 2018 emissions.

Baseline scenario

- The baseline scenario is a continuation of current trends: it represents a 'business as usual' world in which no additional efforts are taken on stabilising the atmospheric concentration of GHGs.
- Overall climate and energy policy goals are:

	2030	2050	Ref year
Renewable Energy	>27%	31%	-
Primary Energy	-23% (-30%)	-20%	2005 (2030)
CO_2 total	-40%	-48%	1990
CO_2 total	-36%	-44%	2005
Emissions Trading Scheme (ETS)	-43%	-62%	2005
Non-ETS	-30%	-28%	2005

- The EU is assumed to reduce its energy related CO_2 emissions **by 48% by 2050**, as in the EU Reference Scenario 2016.

Diversified scenario (Div1)

The EU is assumed to use all known supply, efficiency and mitigation options, including CCS and new nuclear plants. The Diversified scenario has a long-term decarbonisation target of 80% below 1990 levels in 2050.

ProRES scenario (Res1)

Same as Diversified scenario except that there are no new nuclear plants and no underground storage of CO_2.

3.2 Comparison with other EC scenarios

The EUCO30 scenario from the European Commission [13] has a similar 80% GHG reduction and falls between the Diversified and ProRES scenario. This is due to the diverging assumptions in both scenarios. The amount of variable renewables of the Baseline scenario is consistent with the EU Reference Scenario 2016. The sensitivity RES7_Near_ZeroCarbon has an overall CO_2 target that is more stringent and is expected to be closer to one of the scenario produced in the ongoing exercise EU Long-term greenhouse gas emissions reductions Strategy.

4 JRC-EU-TIMES specific assumptions

The model follows the energy system of the EU 28 and of neighbouring countries from the years 2010 to 2060. It produces projections (or scenarios) of the EU energy system under different sets of specific assumptions and constraints. In this function, the model is used for a number of research activities at JRC and for the Horizon 2020 project "Heat Roadmap Europe 2050" [14]. Many assumptions of JRC-EU-TIMES (such calibration, nuclear energy and demand projections) are described in [9], [15] and [14].

JRC-EU-TIMES is an improved offspring of previous European energy system models developed under several EU funded projects, such as NEEDS [16], RES2020 [17], REALISEGRID [18], REACCESS [19] and COMET [20]. JRC was partner in the NEEDS project in which the Pan European Times model was originally developed. Since then, the original project partners have developed different versions of the original model some of which are being used for EU funded research projects[1]. The JRC-EU-TIMES model has been further developed over the last years and is currently maintained by JRC unit C.7. One of the scenarios of JRC-EU-TIMES is always aligned to the latest EU reference scenario. The model can be used to assess which technological improvements are needed to make technologies competitive under various low-carbon energy scenarios.

JRC-EU-TIMES follows the paradigm of the TIMES model generator from the ETSAP Technology Partnership of the International Energy Agency, which combines a detailed technology specification with an optimisation approach [21].

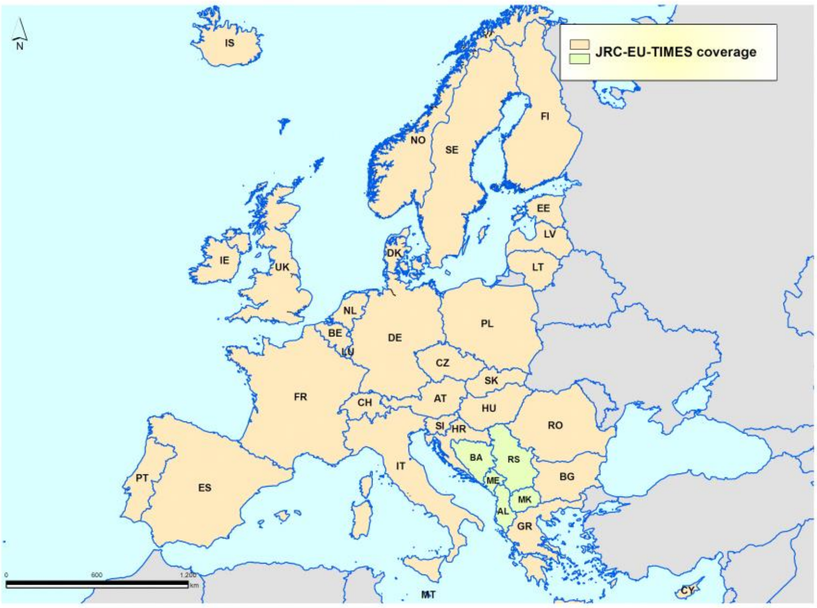

Figure 4. Regions considered in JRC-EU-TIMES

The model solves for the cost optimum investment portfolio of technologies for the entire period under consideration[2], along the supply chains for five sectors, while fulfilling the energy-services demand. This implies simultaneously deciding on asset investments and operation, primary energy supply and energy trade.

[1] E.g. the REEEM project (http://www.reeem.org/)

[2] The TIMES paradigm also allows for alternative approaches such as limited foresight, see [8].

4.1 Renewable Resources

The potential for both wind onshore and wind offshore has been taken from [22]. For geothermal energy, each country has a sustainable potential based on heat in place. The sustainable potential in the EU-28 was assumed to be 5171 PJ for total heat [23]. Using sustainable potential as a limiting factor results in a much lower production than other models that use only technical or economic potential, yet geothermal energy still represents a significant contribution to the energy mix. The sustainability of production could further be improved with the development of hybrid power plants, i.e. using combinations of geothermal and other renewable energy sources to increase the efficiency of power generation. Also, it is important to note that the model assumes that EGS technologies will be proven under various geological conditions and therefore usable in most EU countries. Without EGS, the sustainable potential would be significantly reduced by 90 %. In the main scenarios, the forestry wood availability is constrained on the basis of the reference potentials as derived in the JRC Biomass project [24] and as used for the forthcoming LULUCF regulation.

Table 2. Potential (PJ) for wood-based forestry commodities for 2050

Country	Potential		Country	Potential		Country	Potential
Austria	57		France	252		Netherlands	5
Belgium	18		Greece	12		Norway	84
Bulgaria	16		Croatia	12		Poland	56
Switzerland	34		Hungary	25		Portugal	27
Cyprus	0		Ireland	5		Romania	63
Czech Republic	19		Iceland	0		Sweden	140
Germany	149		Italy	78		Slovenia	13
Denmark	10		Lithuania	19		Slovakia	8
Estonia	18		Luxembourg	1		United Kingdom	27
Spain	55		Latvia	37			
Finland	51		Malta	0			

4.2 Technology limitations

To model an expected inertia in the transition to electric cars, there is a maximum share of electric vehicles (EV) and plug in electric vehicles (PHEV) cars in the new fleet as, in line with the assumptions made by Bloomberg for their New Energy Outlook[3].

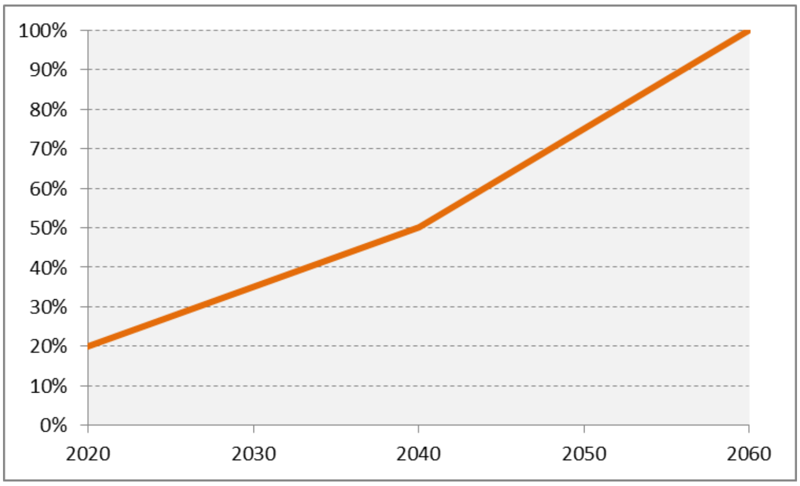

Figure 5. Maximum adoption rate for EV modelled as a share of new bought cars

4.3 Discounting

For discounting future cash flows, the JRC-EU-TIMES model follows a hybrid approach. Within a given time period, costs of capital are differentiated by technology and between businesses and households as shown in **Table 3**. The technology-specific discount rates are the ones used in the PRIMES model for the EU Energy Roadmap 2050. For weighting costs across the different modelling periods, a social discount rate of 5% is used.

Table 3. Discount rates in JRC-EU-TIMES

Sector/group of technologies	Discount rate	Sector/group of technologies	Discount rate
Passenger cars	17.5%	CHP and industry	12%
Freight transport	12%	Centralised electricity generation	9%
Busses and passenger trains	8%	Geothermal electricity generation	12%
Residential	10%	CCS and CCUS	12%
Commercial	9%	Energy distribution	7%
Retrofitting of buildings	9%		

[3] https://about.bnef.com/new-energy-outlook/

4.4 Assumptions on Direct Air Capturing

Direct Air Capturing (DAC) was introduced in JRC-EU-TIMES. Energy consumption and Capex are mostly taken from [25] and steady improvements to the target value of 300 €/ton is assumed. Data used is shown in **Table 4**. DAC is yet to be proven on a large scale. There is a wide range of cost estimates from 200 $/ton of CO_2 to even 1000 $/ton and even ambitious targets of 30-60 $/ton with large scale deployment. Various technologies are available including absorption in a sodium hydroxide solution or adsorption (Temperature swing adsorption (TSA), temperature-vacuum swing (TVS), pressure swing adsorption (PSA), vacuum swing adsorption (VSA), and electrical swing adsorption (ESA)). There are already various efforts of demonstration on large scale by companies like Climeworks (Switzerland), Carbon Engineering (Canada) and Global Thermostat (US). The deployment of a 900 ton per year plant was already achieved in 2017[4], but significant learning is needed to de-risk the technology. A fundamental problem is the large increase in energy requirement associated to the lower CO_2 concentration in air (497 kJ/kg CO_2 for air vs. 172 kJ/kgCO_2 for flue gas from a power plant), which leads to an equal steep escalation of the capture cost.

Table 4. Techno-economic parameters used for Direct Air Capture (DAC).

Parameter	Units	2015	2020	2030	2050
Electricity input	GJ/ton CO_2	2.5	2	1.6	1.28
Heat input	GJ/ton CO_2	11.5	9.2	7.36	5.89
Capex	€/ton CO_2	600	480	384	307.2

[4] http://www.sciencemag.org/news/2017/06/switzerland-giant-new-machine-sucking-carbon-directly-air

5 Scenario sensitivities

The scenarios and sensitivities have been developed for the LCEO AA following a workshop that took place in September 2017.

5.1 Overview of all scenarios and sensitivities

Each global storyline comes with a scenario: Baseline, Diversified and ProRES. For the decarbonised scenarios, sensitivities have been designed on three levels: technology learning, resources and policies. All are explained separately in this chapter.

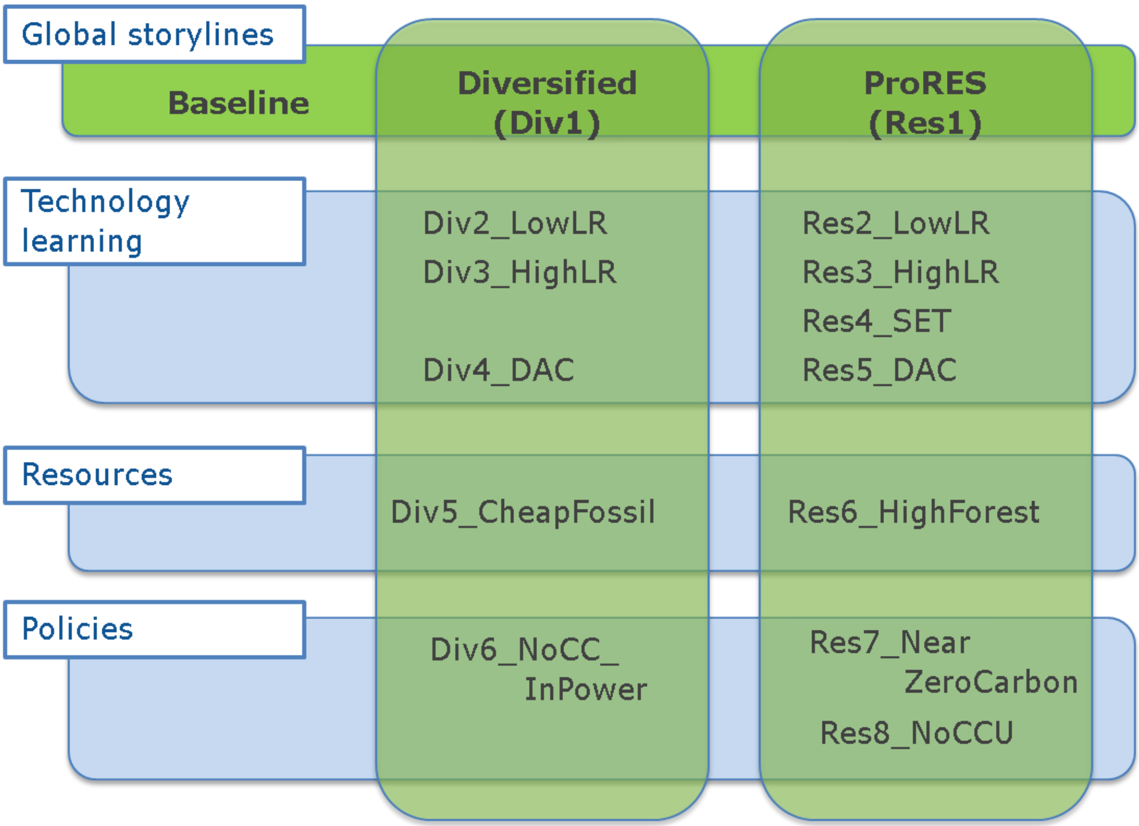

Figure 6. Overview of all scenarios and sensitivities

The table below gives an overview of how the 16 scenario and sensitivities compare. All scenarios have the option of a lifetime extension of existing nuclear power plants up to 60 years in the countries without a phase-out policy. All scenarios have CCU reuse except RES8_NoCCU.

Table 5. Overview of some key characteristics from all scenarios and sensitivities

NAME	LEAR-NING	CO2 2050	NUC +20yr	NEW NUC	CO2 STOR	CO2 REUSE
Baseline	REF	-46%	YES	YES	YES	YES
Div1	REF	-80%	YES	YES	YES	YES
Div2_LowLR	LOW	-80%	YES	YES	YES	YES
Div3_HighLR	HIGH	-80%	YES	YES	YES	YES
Div4_DAC	REF	-80%	YES	YES	YES	YES
Div5_CheapFossil	REF	-80%	YES	YES	YES	YES
Div6_NoCC_InPower	REF	-80%	YES	YES	YES	YES
Res1	REF	-80%	YES	NO	NO	YES
Res2_LowLR	LOW	-80%	YES	NO	NO	YES
Res3_HighLR	HIGH	-80%	YES	NO	NO	YES
Res4_SET	SET	-80%	YES	NO	NO	YES
Res5_DAC	REF	-80%	YES	NO	NO	YES
Res6_HighForest	REF	-80%	YES	NO	NO	YES
Res7_Near_ZeroCO2	REF	-95%	YES	NO	NO	YES
Res8_NoCCU	REF	-80%	YES	NO	NO	NO

5.2 Technology learning

The learning rate method resulted in sensitivities with lower and higher learning rates: Div2_LowLR, Div3_HighLR, Res2_LowLR and Res3_HighLR. Additionally, there is one specific sensitivity where EU technology innovation is made consistent with the targets of the SET Plan (Res4_SET). For some key technologies, the CAPEX and Levelised Cost Of Electricity (LCOE) are given in Annex 2-7. The LCOE is derived from data that are inputs to JRC-EU-TIMES but is not an input itself. The LCOE does not take into account the total impact on the power system and is for that reason only an indicative cost indicator.

The learning assumptions and derived CAPEX can be found in the technical report prepared by the JRC [12]. Specifically for the SET Plan scenario, we provide an overview of the assumptions for each technology:

- Ocean: following SET-Plan targets are included:
  - Tidal: reaching 100 EUR/MWh by 2030
  - Wave: reaching 150 EUR/MWh by 2030
- PV: following targets have been included:
  - Efficiency improvement by at least 20% by 2020 and 30% by 2030 compared to 2015. In JRC-EU-TIMES, efficiency of PV translates to surface area. Hence, improved efficiency leads to lower surface area used.
  - CAPEX: reduction of CAPEX by 20% in 2020 and 50% in 2030 compared to 2015
  - Increase lifetime to 30 years by 2020 and 35 years by 2025
- PVT: the target to reduce CAPEX by 40% by 2020 was included.
- Wind: the Res scenario is in line with the SET Plan targets:
  - LCOE of offshore wind less than 10 ct./kWh by 2020 and less than 7 ct./kWh by 2030.
  - For deep waters (>50m) and distances 50 km. LCOE if 12 ct./kWh for 2025 and 9 ct./kWh for 2030
- Geothermal: the target to reduce CAPEX by almost 50% by 2050 was included.

Two more sensitivities (Div4_DAC and Res5_DAC) include more optimistic assumptions for the CAPEX of Direct Air Capturing. The CAPEX of the DAC sensitivity is based on an article [26] that suggests that the DAC costs might be cheaper than expected (Levelized costs of $94 to $232 per ton CO_2 from the atmosphere). It is the first DAC paper with commercial engineering cost breakdown.

5.3 Resources

5.3.1 Cheaper fossil fuel

Cheap fossil is a sensitivity that was agreed upon and we assume that the price of oil gradually declines to its lowest value of 40 $2010 per barrel. The reduction of the gas price is assumed to be equal of that of oil.

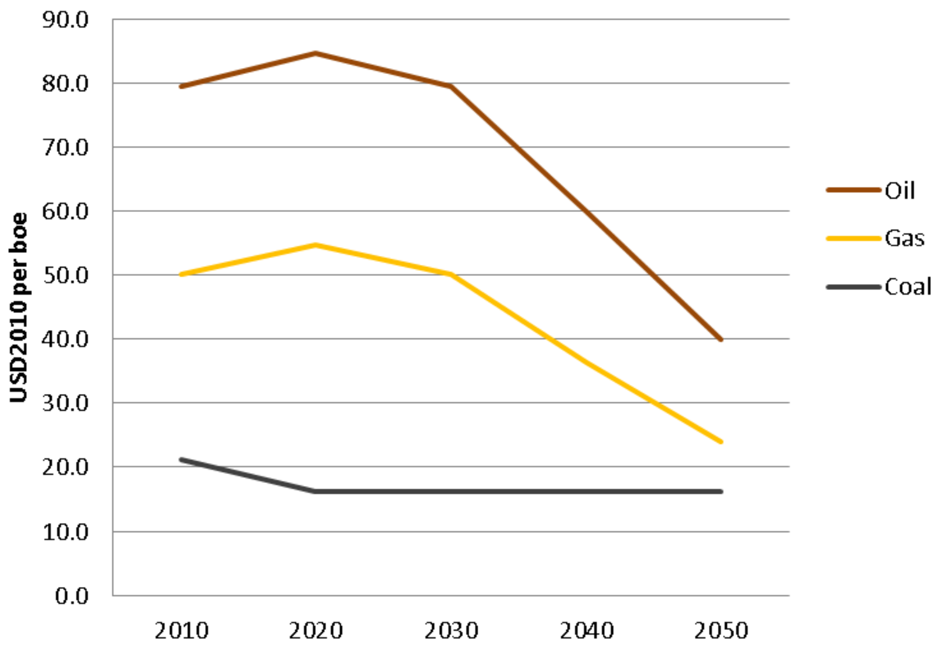

Figure 7. Assumption of the fossil prices in the sensitivity Div5_Cheap Fossil

5.3.2 Higher forestry biomass potential

A sensitivity run was done for the forestry biomass potential. A high mobilization scenario (HM) has been used. The forestry biomass availability in this scenario has been formulated assuming that "the full forest harvest potential is exploited for material and/or energy purposes, under equilibrium conditions for the forest, i.e. the forest exploitation will result CO_2 neutral, not being a sink nor a source of carbon". In this way, the forest biomass availability shown in **Table 6** will be over the reference levels considered in the proposal for a LULUFC directive (COM/2016/0479 final - 2016/0230 (COD)), if historical reference levels based on increasing sinks would be adopted. The potential debit CO_2 resulting from fully using these potentials can be compensated by other LULUCF sectors (such as afforestation) or by other finally approved flexibility mechanisms. Secondly, wood pellets apparent consumption for the whole of EU as modelled by GFTM is forced to double between 2015 and 2030, reaching a level of 40 million tons by 2030. We deem this increase, though steep, as being plausible. In GFTM, for all other wood-based commodities within the EU and for all commodities outside the EU, projections of production, trade and apparent consumption are derived as solutions to the welfare-optimization problem under resource, technology and equilibrium constraints, without the addition of any further exogenous assumption. Table 6 illustrates de total maximum energy potential available from forestry products for 2050, as considered for the Baseline.

Table 6. Potential (PJ) for wood-based forestry commodities for 2050, increased harvesting

Country	Potential		Country	Potential		Country	Potential
Austria	128		France	275		Netherlands	26
Belgium	40		Greece	37		Norway	135
Bulgaria	99		Croatia	78		Poland	122
Switzerland	63		Hungary	65		Portugal	100
Cyprus	0		Ireland	48		Romania	105
Czech Republic	82		Iceland	0		Sweden	475
Germany	302		Italy	221		Slovenia	32
Denmark	38		Lithuania	76		Slovakia	39
Estonia	50		Luxembourg	4		United Kingdom	88
Spain	199		Latvia	79			
Finland	145		Malta	0			

5.4 Policies

5.4.1 Technology policies on carbon capturing and utilisation

Two specific sensitivities were created that restrict in some way CCUS. In the first one (Div6_NoCC_InPower), carbon capture is not deployed in the power sector. This represents a policy in which RES is given priority for electricity production without hampering the deployment of CCS in the industrial sector or in the production of alternative fuels. In the second one (Res8_NoCCU), the utilisation of CO_2 is restricted on top of the geological storage restriction that was already in place in the ProRES scenarios. This scenario allows to understand the value of reusing CO_2.

5.4.2 A near zero carbon energy system

One sensitivity is for analysing the impact of further reducing CO_2 in the energy system. This variant of the ProRES scenario has a long-term decarbonisation target of 95% below 1990 levels in 2050.

6 Decarbonising the EU energy system

Both chapter 6 and chapter 7 present results for the different scenarios and sensitivities. The focus of this report is the overall transition of the energy system for a better understanding of the deployment of individual technologies. The impact of the different sensitivities (technology learning, resources and policies) is included in each individual result when it has a relevant impact.

6.1 CO_2 emissions

- In the Baseline scenario, CO_2 reduction mainly comes from the power sector. Total emission reduction amounts to 42% already in 2030 compared to 1990. This reduction is equivalent with a 35% reduction with respect to 2010.
- Beyond 2030, there is no further CO_2 reduction which is remarkable given that RES technologies become ever cheaper through global learning. One explanation is that energy services demands still increase beyond 2030. Another explanation is that the share of wind and solar doesn't easily surpass a threshold of 35-40% in the electricity production. With such level, the average electricity price received by wind and solar can be as low as 50% of the price paid to dispatchable power plants. Above the threshold, storage in different forms such as hydrogen is required, a technology that is only playing a small role in the Baseline (2% of the electricity is converted into hydrogen). Above such threshold, even cheaper RES is needed to further increase its share, even if a CO_2 price of 100 EUR/tonne or more would be established.

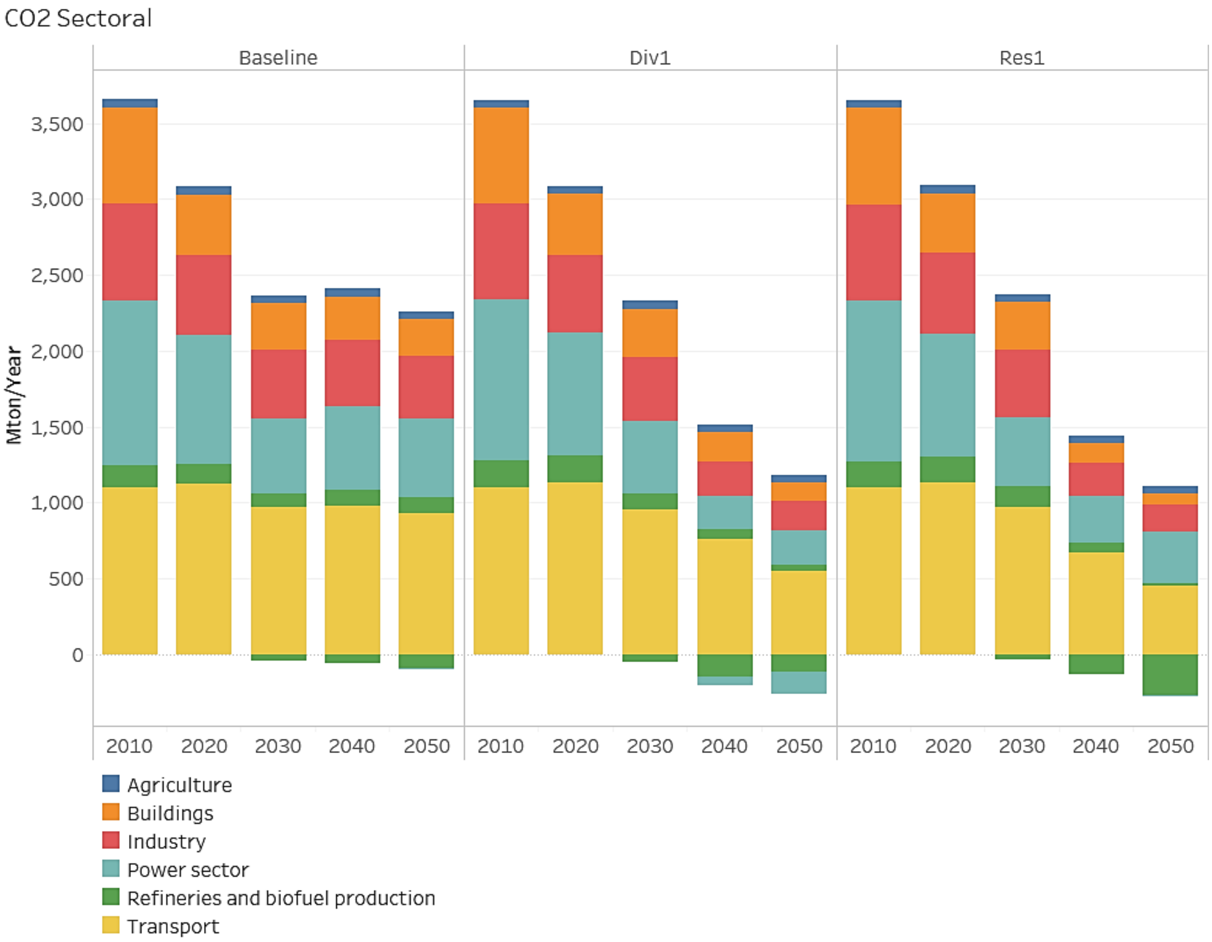

Figure 8. JRC-EU-TIMES result: EU energy related CO_2 emissions

- In the Diversified and ProRES scenarios, the 80% reduction of CO_2 compared to 1990 brings EU emissions down to 900 Mton. The reduction is the strongest in the power sector.
- In the Diversified scenario negative emissions occur with biomass based power production as the main contributor.
- In the ProRES scenario, CO_2 cannot be stored under the ground. The CO_2 that is a by-product from second generation biofuel, is used to produce electrofuel and is emitted again within the transport sector.

6.2 CO_2 capturing, storing and reusing

- In all scenarios, CO_2 is captured. Permanent storage of CO_2 occurs in the countries where underground storage of CO_2 is allowed in the Baseline and Diversified sensitivities.
- In the **Diversified scenario**, the carbon entering the energy system decreases by 60%, down to 2500 Mton. From this 60%, again 60% (almost 1500 Mton) is captured and stored permanently underground. The part that is not stored is finally emitted as CO_2.
  - Almost 60% of the total CO2 is stored or used, mostly captured from power production or fossil based hydrogen or collected as a by-product from the production of 2nd generation biofuels.
  - Additional CO2 is also directly captured from the air (at least 100 Mton per year).
  - Permanent storage of CO2 occurs in the countries where underground storage of CO2 has not been restricted yet.
  - Cement is the largest industrial source, as no hydrogen alternative was included in JRC-EU-TIMES.
  - Hydrogen is produced mainly from gas with CCS.
  - Such transformations would require a rapid scale-up of CCS technologies.
- In the sensitivity where carbon capture is not deployed in the power sector (**Div6_NoCC_InPower**), more CO_2 is captured from
  - fossil based hydrogen production, i.e. coal gasification and steam methane reforming.
  - 2nd generation biofuel production
- In the **ProRES** scenario (RES 1) there is no option to permanently store CO_2 under the ground.
  - More than 400Mton/year CO_2 is still captured and reused.
  - The main use of this CO_2 is the production of diesel/kerosene by combining hydrogen and CO_2.
- In the sensitivity with 95% reduction of the CO_2 (**RES7_NearZeroCarb**), more than 50% of the CO_2 captured is reused.

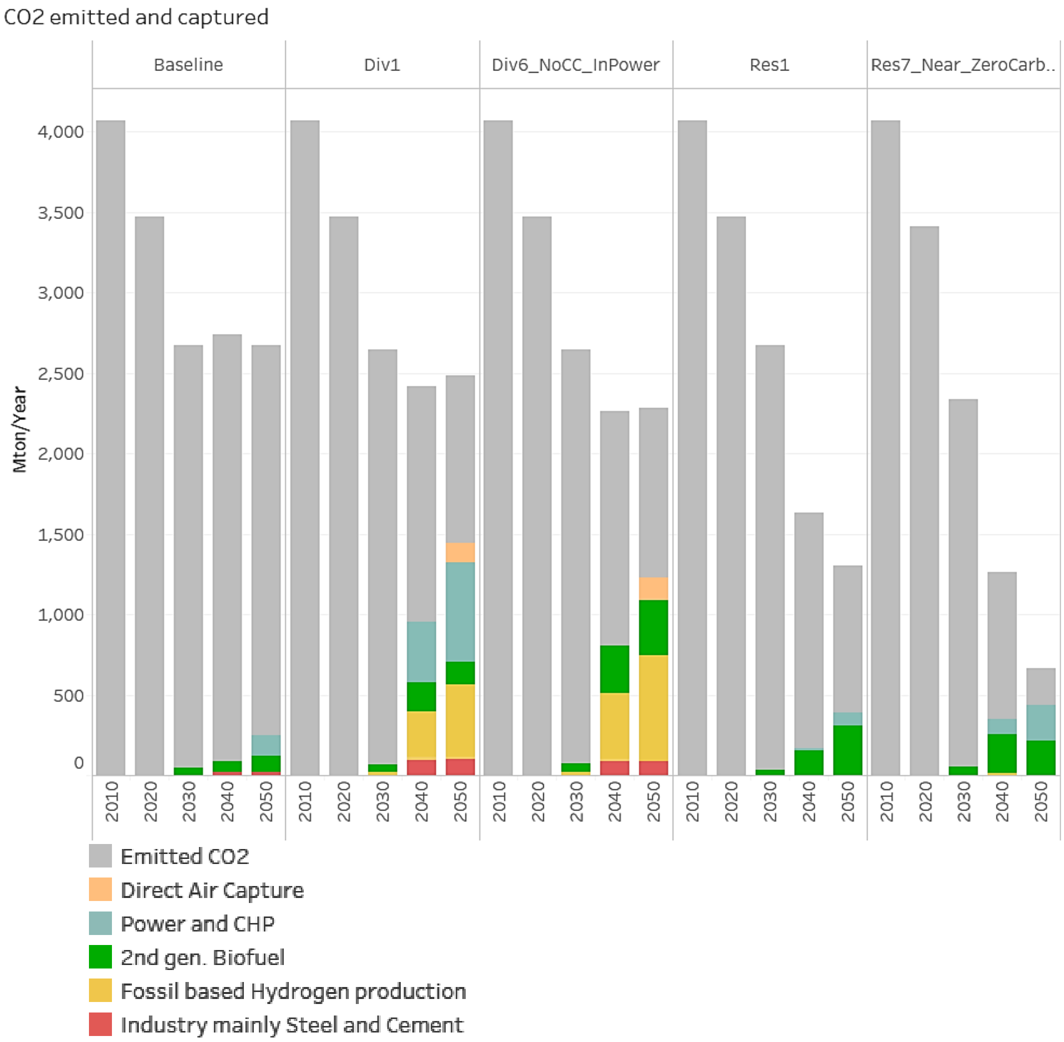

Figure 9. JRC-EU-TIMES result: emitted and captured CO_2 emissions

Reusing captured CO_2

CCUS is the name for a family of processes that enables the capturing, utilisation and storage of CO_2. In the ProRES scenario, one third of the carbon entering the system is captured and later used again allowing double use of the same amount of carbon. In this case, the CO_2 is stored only for a short period, in contrast to long term underground storage.

What are electrofuels ?

In the context of this report, Electrofuels refers to liquid fuels that are produced from electricity and CO_2. In the ProRES scenario, liquid electrofuels are almost entirely produced from renewables and are being used by trucks, planes and industries. The CO_2 that is used has been captured mainly in the production biofuels. Eelectrofuels are sometimes referred to any fuel that is made from electricity (including hydrogen from electrolysers)

6.3 Energy mix and energy efficiency

- The JRC-EU-TIMES baseline envisions that by 2050
    - Coal consumption is reduced by two-thirds and oil consumption is reduced by a third. Natural gas remains an important energy carrier, with consumption levels similar to 2015 values.
    - From a production standpoint, the RES share of total primary energy production increases from 10% in 2015 to 24% by 2050. The share of variable RES (from wind, solar and ocean) increases from 2% in 2015 to 8%.
    - The share of non-variable RES consists mainly of biomass that will increase from 5% to 9% by 2050.
- In all scenarios plotted, total gross energy use is reduced stemming from remarkable energy efficiency improvements. In the Diversified scenario, the total energy reaches the upper limit imposed while in the ProRES scenario, the shift to renewables drive total energy already below that limit.

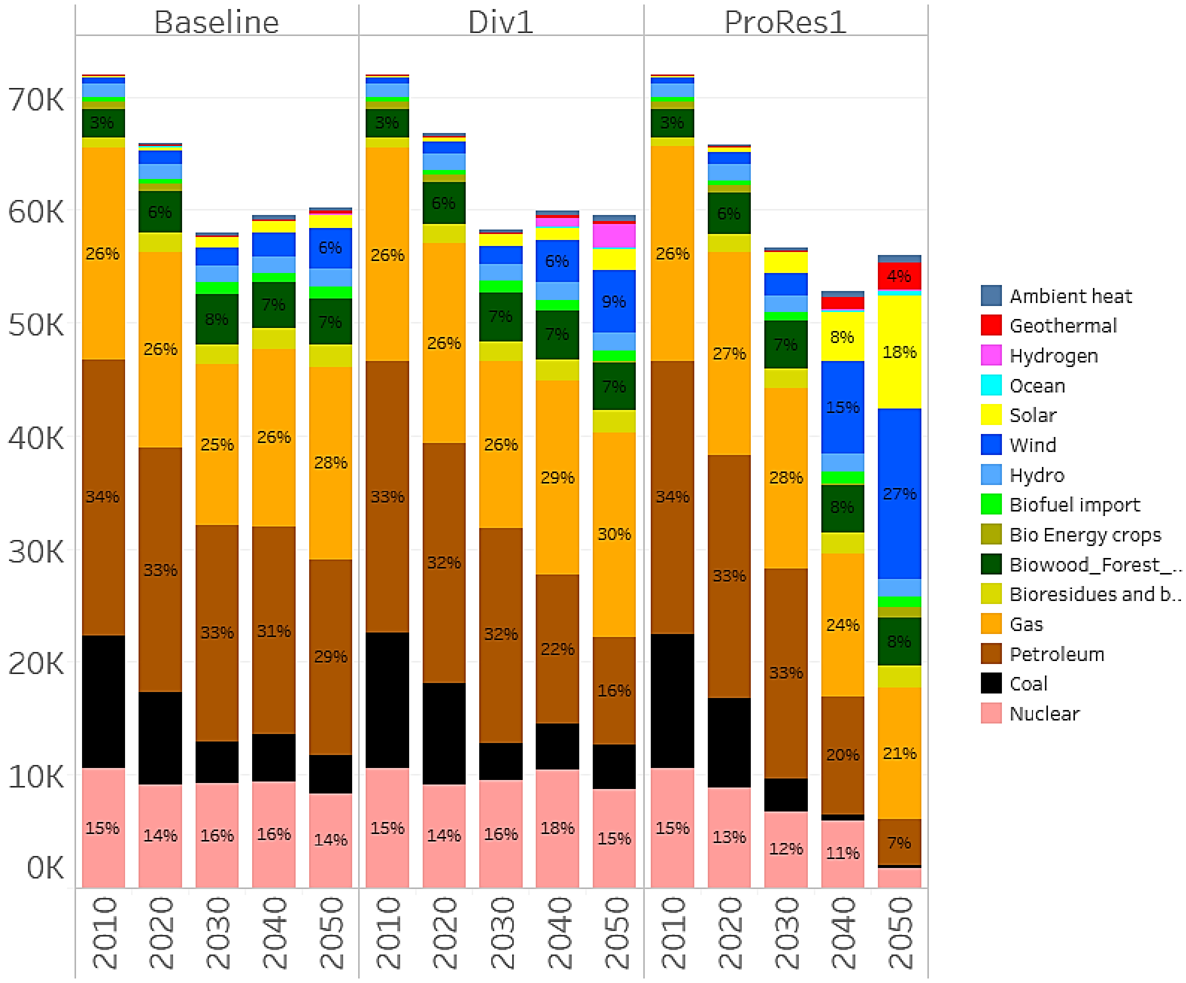

Figure 10. JRC-EU-TIMES result: EU gross energy consumption (PJ)

- In the Diversified scenario, even though it includes an 80% reduction target of CO_2, a similar mix is seen as in the baseline scenario for nuclear, coal and gas. However, oil consumption is reduced by 60%, twice the reduction seen in the Baseline scenario. Oil is replaced by a similar amount of variable renewable as well as imported hydrogen, coming mainly from Norway.
- In the ProRES scenario
  - The share of nuclear in 2050 reaches only 15% of today's levels, even though this scenario includes a lifetime extension of existing nuclear power plants up to 60 years in the countries without a phase-out policy.
  - 70% of the gross energy comes from renewable sources.
  - All forms of renewables are deployed and complement each other.
  - Biomass and hydro used up to their technical, sustainable potential. The other renewable resources (wind, solar, geothermal and ocean) are used up to the economic optimum.

6.4 Final Energy use

- Today
  - Oil primarily supplies transport and less the buildings sector (residential & commercial). Gas on the other hand is directly used by the buildings sector, industry and for power generation. The contribution of renewables in inland consumption is around 13%.
  - Sectorial consumption of final demand: in order of contribution the energy sectors that consume most energy are buildings (¬43%), transport (¬32%) and industry (¬25%).
  - About a tenth of total electricity is generated by wind and solar. Their share is less than 2% in total energy consumed in the EU.
  - Road transport consumes the bulk of the transport sector's energy (80%) and is predominantly oil (95%) –the remainder is biofuels.
  - 50% of final energy is Heating and Cooling.
- Baseline
  - In the baseline scenario the final energy used for heating and cooling decreases with 23%. Coal and oil boilers are gradually abandoned in buildings, while biomass displaces fossil fuels in the industry.
  - The total final energy used for heating and cooling decreases by 23% by 2030, from 7000 TWh in 2010 to 5400 TWh. This 23% decrease is in line with the proposed overall energy efficiency target of 30% target for 2030, bearing in mind the 23% equivalent reduction when compared to historical consumption. After 2030, no more major reduction of energy use is occurring.
  - Due to improvements in building insulation as well as heating and cooling technologies, energy use in buildings decreases by 32% by 2030, from 4100 TWh in 2010 to 2800 TWh. Coal and oil boilers are gradually abandoned.
  - Energy use for heating and cooling in the industry remains relatively stable from 2010 to 2050, but biomass replaces gas, and other fossil fuels.
  - The final energy consumption of residential and tertiary (i.e. commercial and public services) buildings will decrease by 30% and 15% respectively compared to 2015. The most important driving factor for these reductions will be a lower demand for heating largely due to improved energy efficiency and more investment in efficiency measures.

- Diversified
    - Coal and oil are no longer used in buildings
    - Hydrogen is used by trucks and in energy intensive industries (no easy electric alternative)
    - More than 80% of the cars are electric or hydrogen fuelled (driven by significant cost reductions)
- ProRES
    - Buildings are mainly heated with heat pumps (with a renewable share of the heat coming from the air or ground)
- Although the total final energy remains stable or decreases, the strong growth in economic activity is respected. As an example, with the same total amount of energy, the activity of cars, trucks and planes increase by 2050 with respectively 30%, 50% and 100%.

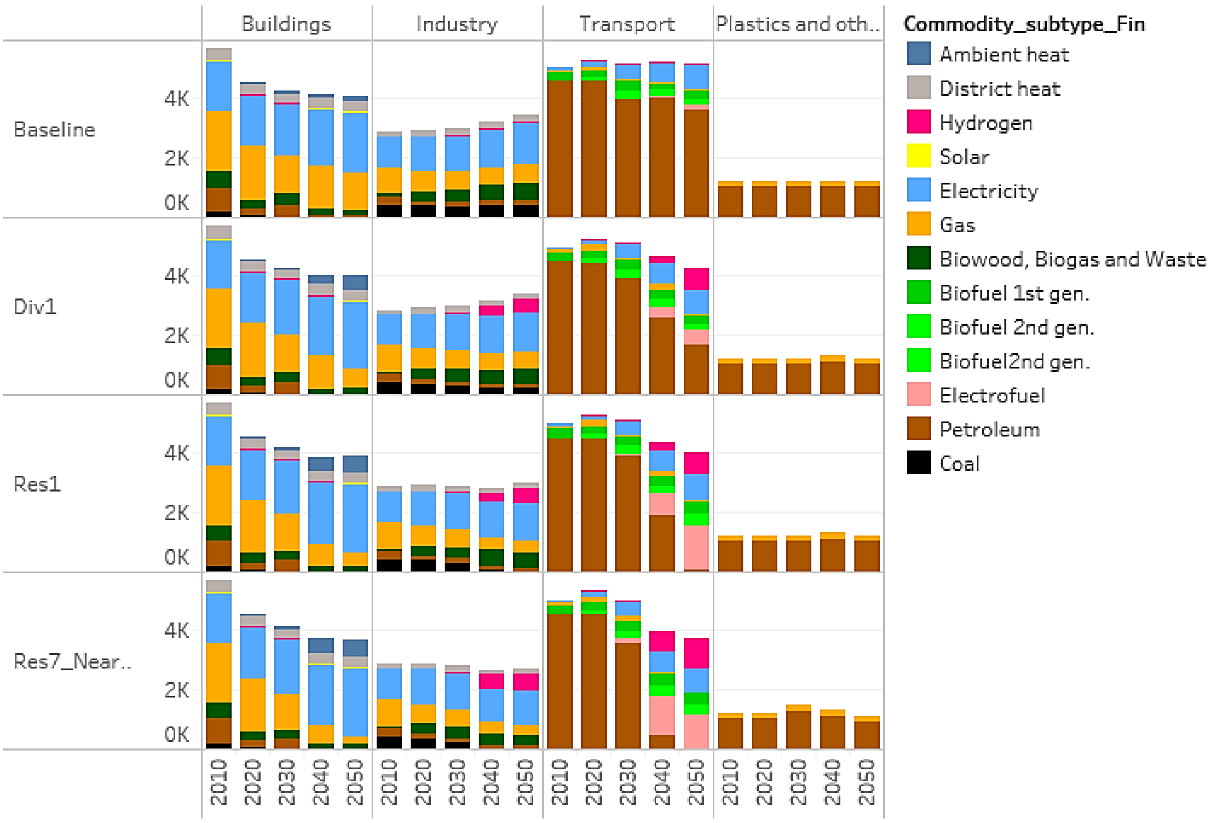

Figure 11. JRC-EU-TIMES result: sectoral EU final energy use (TWh)

6.5 Electrification in the ProRES scenario (RES1)

- In buildings, electrification is strong even though it is not visible from the absolute numbers. Coal and oil boilers experience a dramatic reduction, virtually disappearing by 2050, because of their CO_2 emissions. Heat pumps contribute to the supply mostly with ambient heat.
- In industry, some processes can use electricity in a direct way, others like steel production can use hydrogen.
- Electrification in transport is revolutionary as by 2050, more than 80% of the cars are electric or hydrogen fuelled (driven by significant cost reductions). The JRC-EU-TIMES sees electric vehicles already becoming cost-effective before 2030, largely due to significant cost reductions from improved technologies, especially in batteries. By 2030, around a sixth of all 300 million vehicles in the EU should be fuelled by electricity.
- Most of the fuel that trucks and aviation consume is derived from electricity in the form of hydrogen or electrofuel.

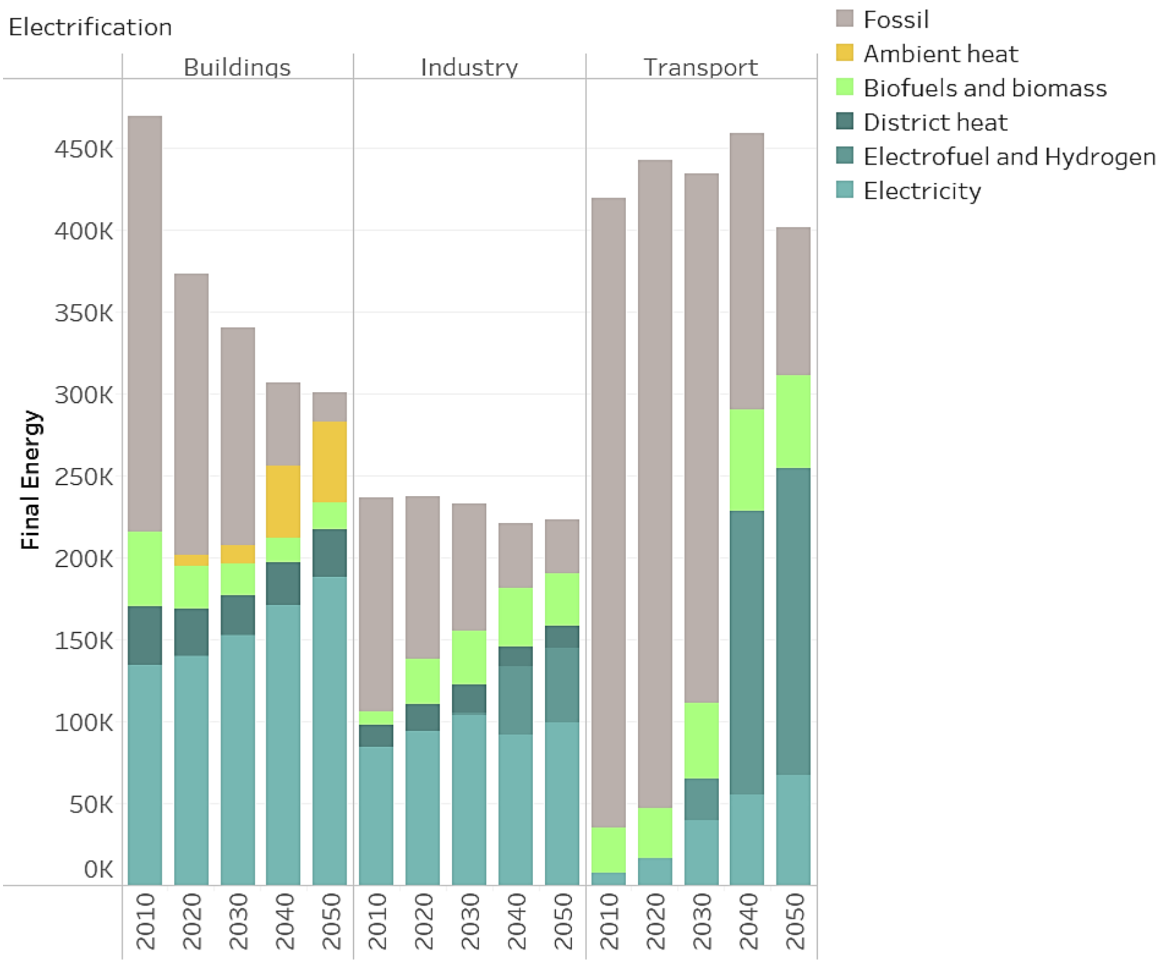

Figure 12. Final energy in the ProRES (ktoe, RES1) Scenario, with a focus on electrification.

6.6 Renewable energy

- The overall renewable energy share is very dependent on the scenario. Low carbon energy technologies greatly contribute to the increase of renewable energies.
- The RES share in 2030 is 28%-30%, close enough to the new target of 32% for the purpose of this analysis which has a focus on 2050.
- Post 2030, there is a slow increase in the baseline reaching 34% and a sharp increase in the decarbonised scenarios reaching 56% and 84% in the Diversified and ProRES scenario respectively.

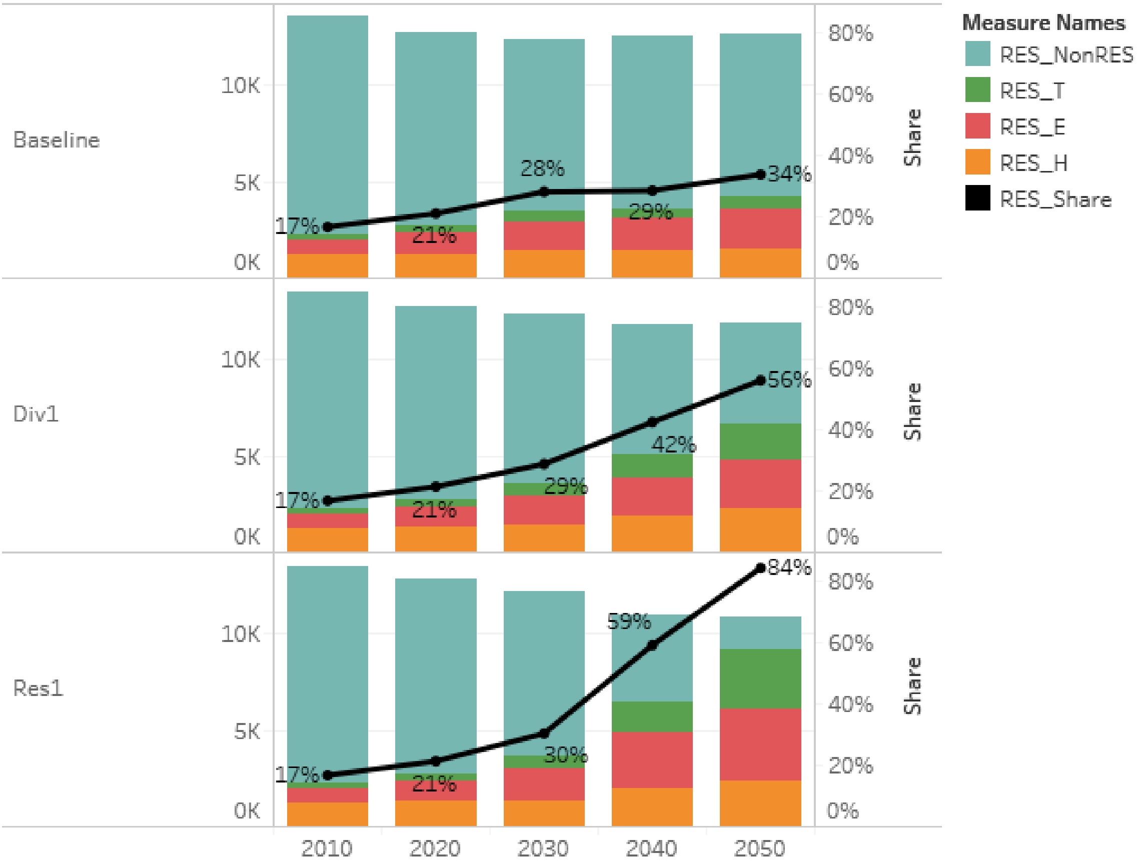

Figure 13. JRC-EU-TIMES result: share of renewable energy, total RES and contribution to the total of RES-E, RES-H, and RES-T

- By 2030, already 42% of electricity will be generated from renewable resources. By 2050, the share of RES-E will be at least 56% up to 84% in the ProRES scenario.
- The strongest increase in terms of RES share is happening in the transport sector. There is an abrupt increase beyond 2020 from as low as below 10% to a maximum of 94% in the ProRES scenario.

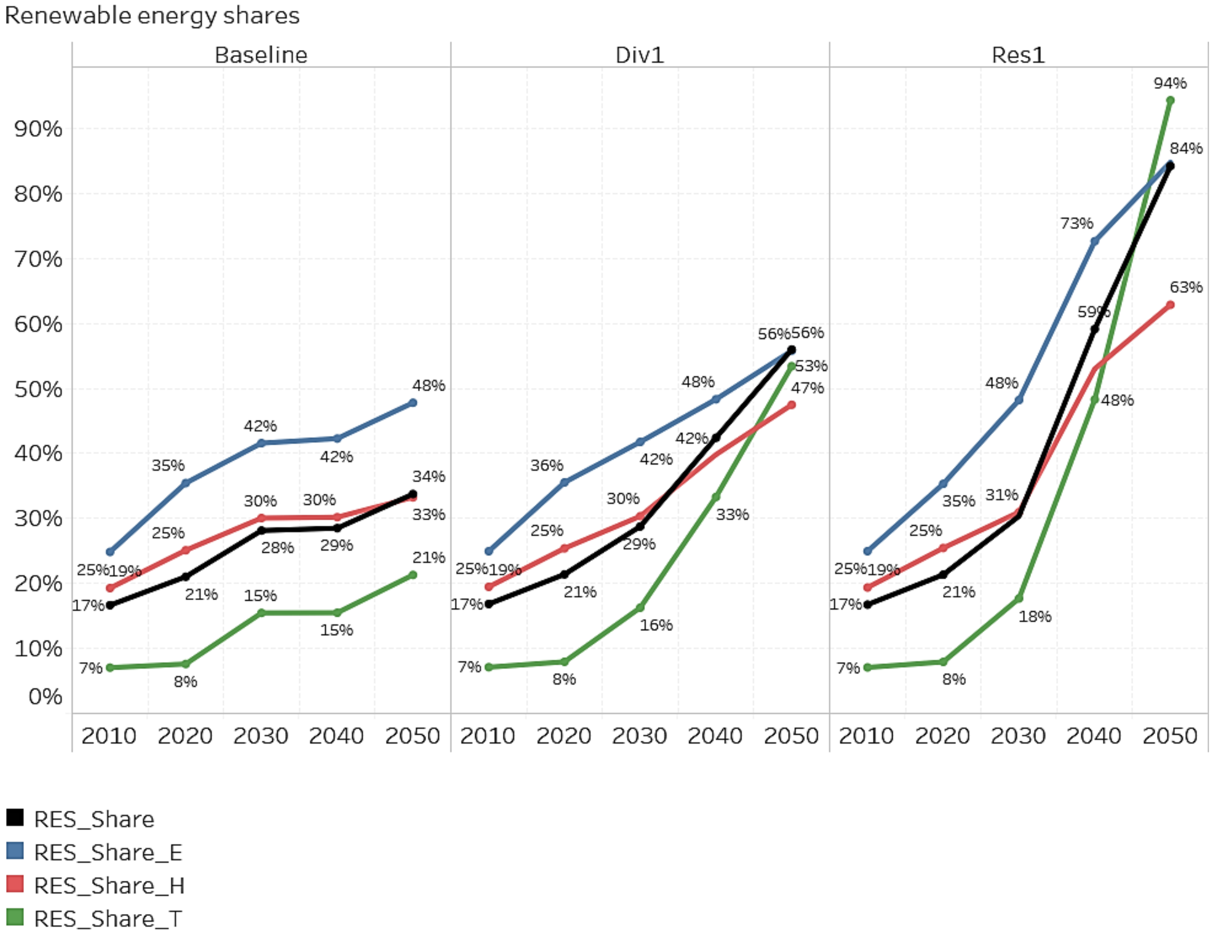

Figure 14. JRC-EU-TIMES result: share of total renewable energy, RES-E, RES-H, and RES-T

6.7 Energy dependency

- In 2016, more than half of the EU's gross inland energy consumption depended on imports (55%), mainly oil and gas. When including also nuclear energy in the indicator, the share was even 75%.
- In 2050, energy important dependency rate is reduced from 75% to 45% in the Diversified scenario (Div1) and to 25% in the ProRES scenario (Res1). The EU energy imports are reduced with respectively 26% and 65% compared to today.

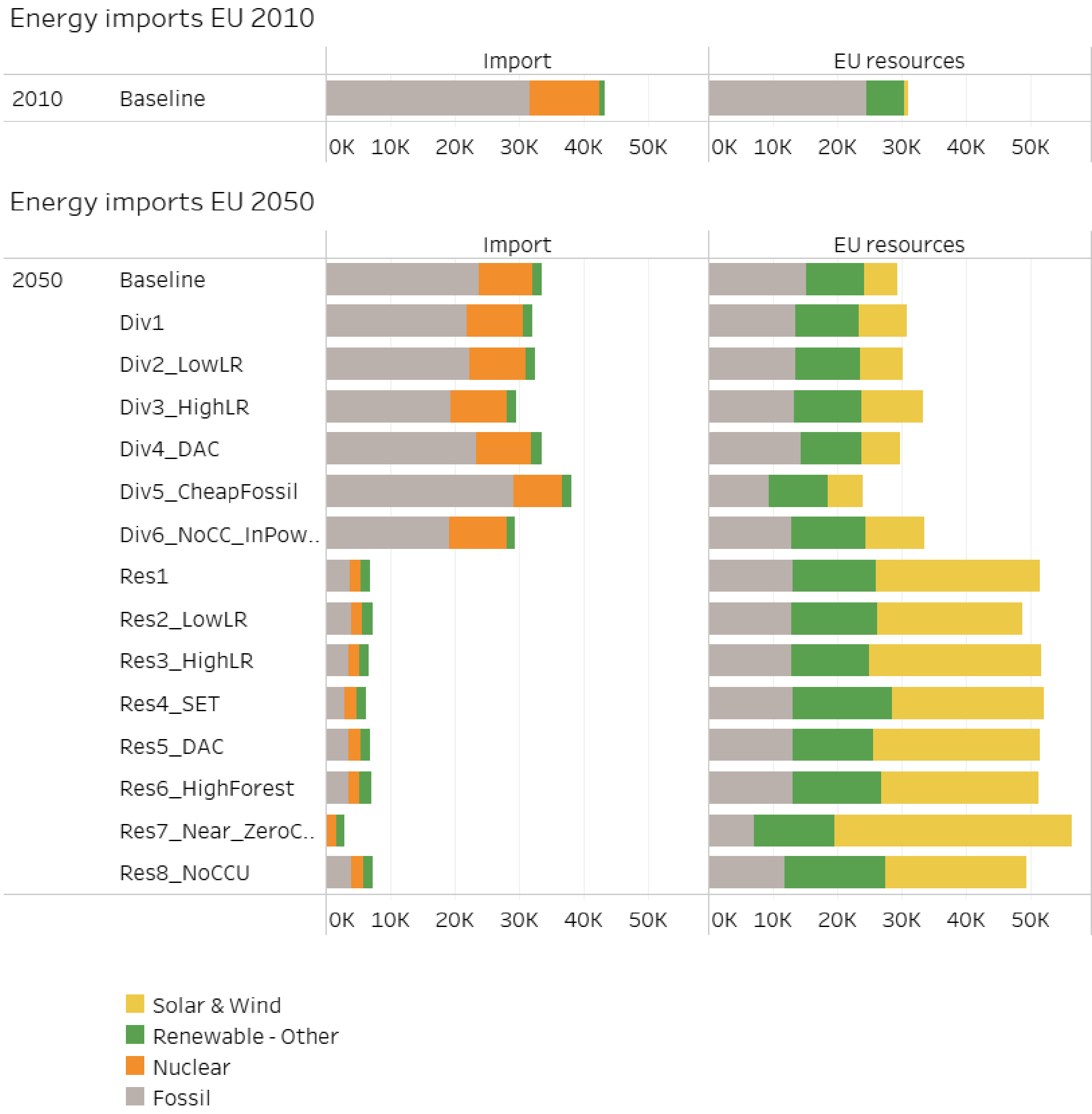

Figure 15. Energy imports and production of energy from EU resources [PJ]. Model results for 2010 may slightly deviate from historical numbers. The right column covers the consumption of energy from mines located in the EU and from EU renewable sources.

7 Outlook for Low Carbon Energy Supply Technologies

7.1 Electricity mix and deployment of Low Carbon Electricity Technologies

- The power sector will steadily increase its production, driven by the electrification of the transport sector. From 2010 to 2050, the amount of installed generation capacity will increase from almost 800 GWe to more than 4000GWe in the ProRES scenario and even more than 6000 GWe in a 95% reduction scenario. Most of this increase can be explained by newly installed PV and wind capacity. PV grows from around 100GWe to almost 2000 GWe, while wind installed power increases from around 150 GWe to 1500 GWe, including 250 GWe of offshore wind.
- Given the described evolution of the energy mix, electricity generation will reflect the corresponding changes. While nuclear generation stays pretty stable, showing even a slight increase by 2030 and 2050, coal generation is almost phased out by 2030.

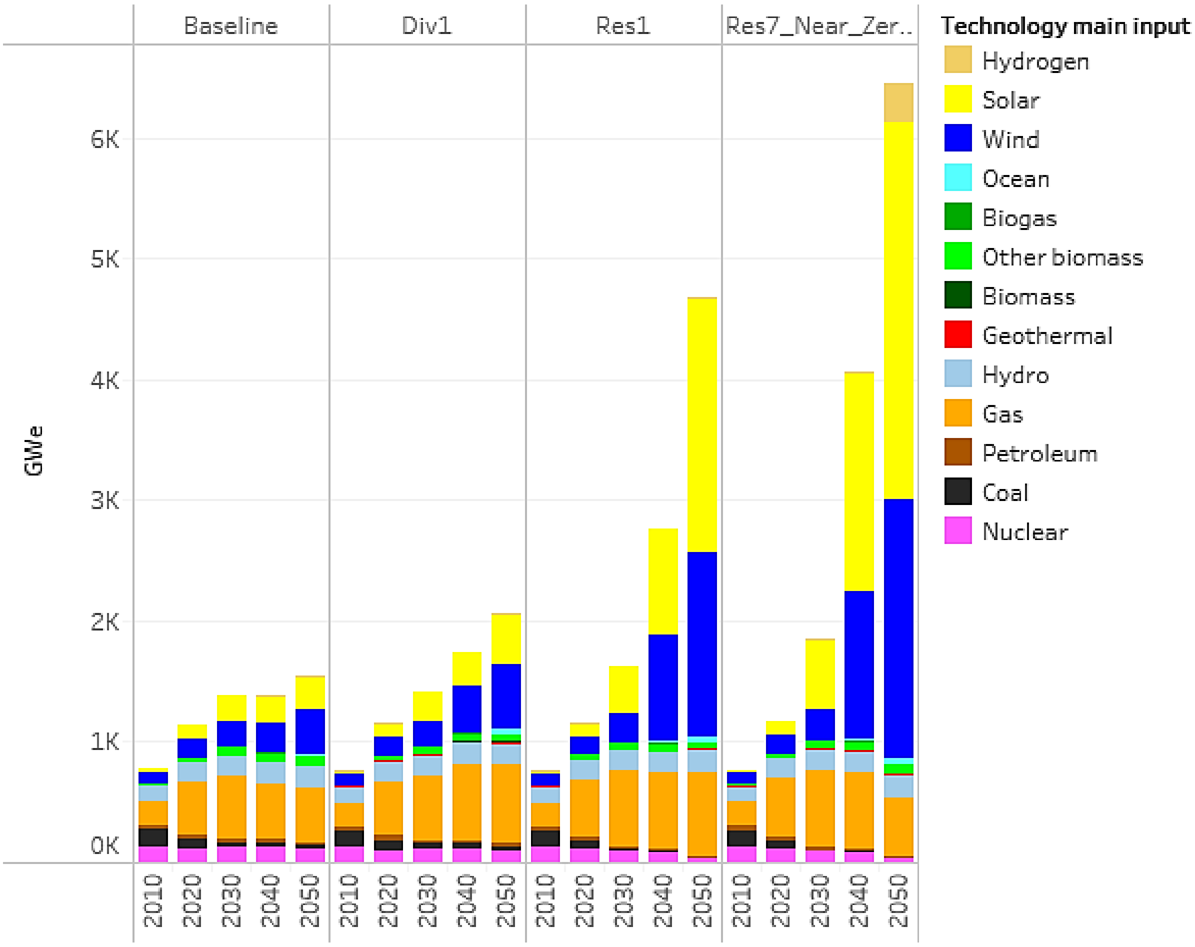

Figure 16. JRC-EU-TIMES result: EU Electricity production (GWe)

- In the ProRES scenario
  - Producing electricity is the largest component in the way renewable resources are used and the electricity production can double compared to today's level.
  - Electricity is largely produced by solar and wind plays a key role and is well inside the range of their potential in the EU. These technologies take the

share of investments but all forms of renewables are deployed (as complementary).

- Photovoltaics (as such also decentralisation) and offshore wind energy boost the sector's supply of renewable energy. This increasing supply of variable electricity requires storage to ensure the reliability of the system.
- The power supply sector is coupled with the transport demand through the increasing sales of private EVs. Heavy duty is also partly based on battery technologies (EV buses) but heavy road transport (trucks), aviation, and shipping remain a bottleneck for transport to decarbonise as there are no easy electric alternatives.
- Hydrogen is produced mainly from electrolysers. It is also deployed in industry and plays a role as a storage option

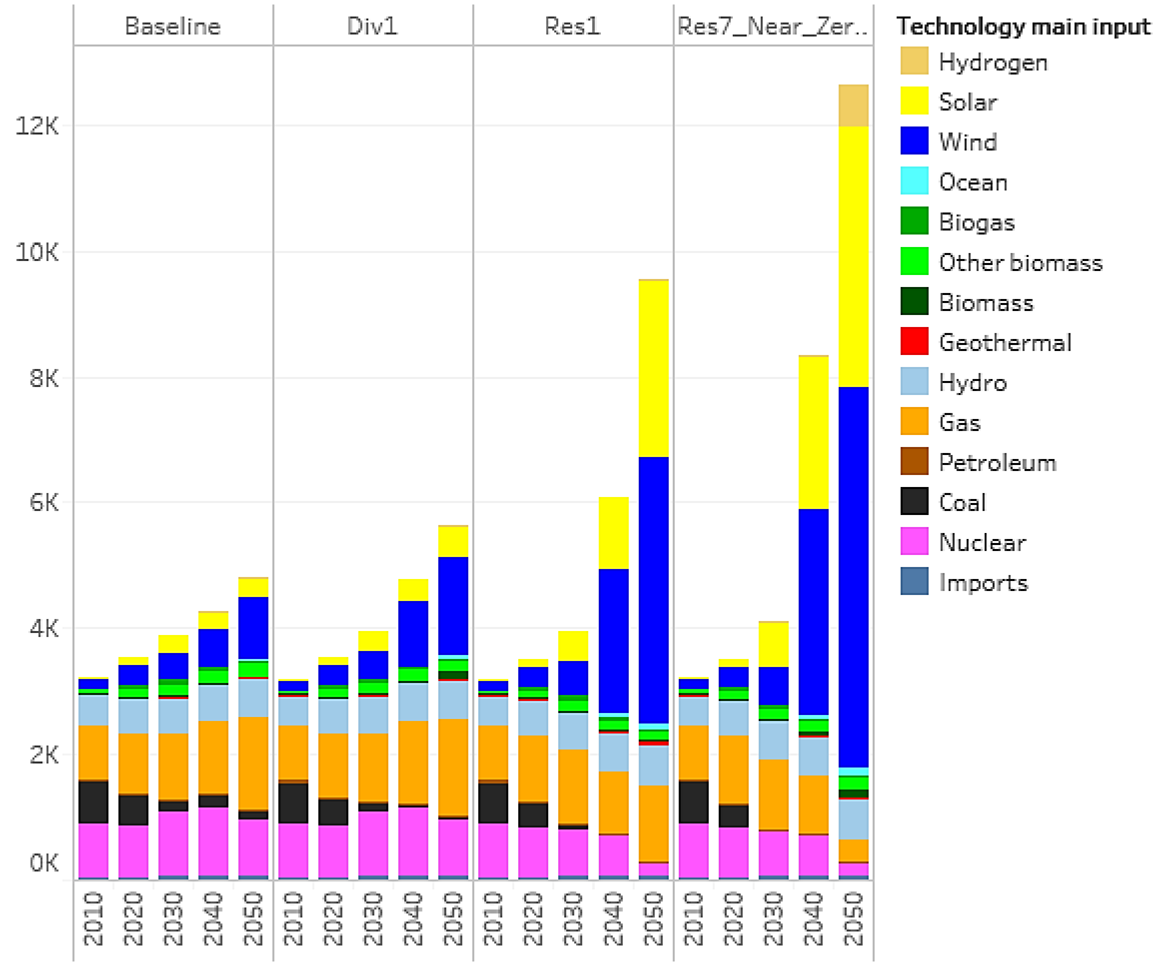

Figure 17. JRC-EU-TIMES result: EU electricity production capacities (TWh)

Figure 17 compares the LCEO results with other studies from within and outside JRC. The closest scenario to the ProRES scenario is the Shell SKY scenario even though it has lower renewable and more nuclear electricity.

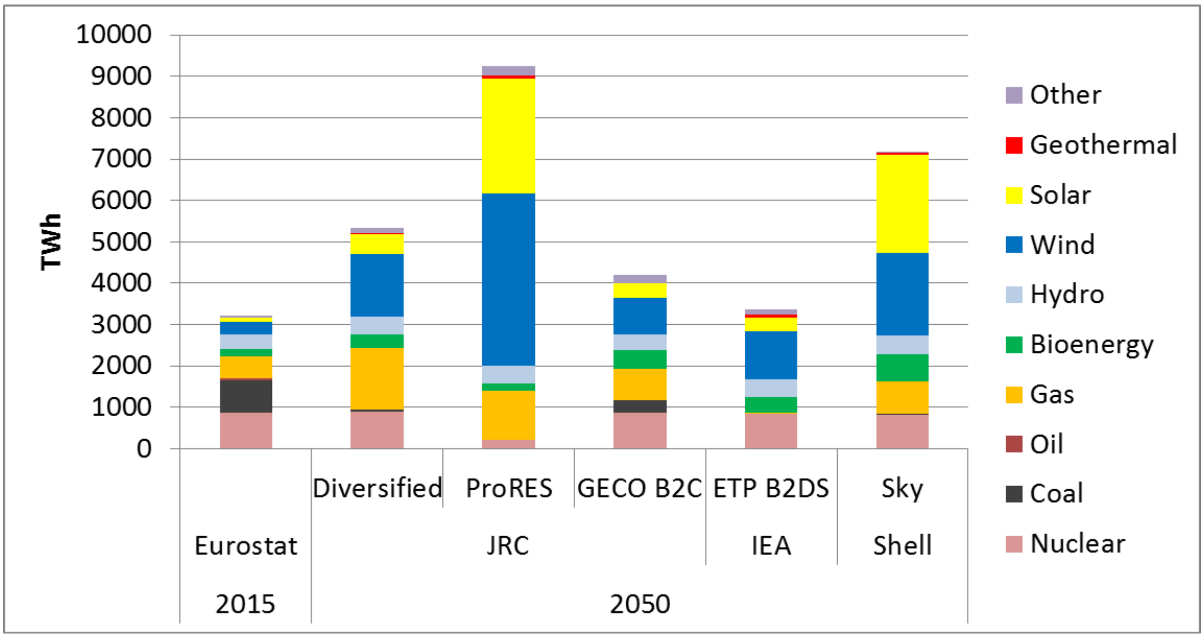

Figure 18. Comparison of the electricity production from Diversified and ProRES scenarios with other studies

7.2 Deployment of Biomass

- Sustainable imports of biofuel (light green) increase and replace in some scenarios the EU production of 1st generation biofuels.
- 2nd generation biofuels increase in all scenarios and is almost always with CCS. The 2nd generation biofuels production is the main user of wood resources.

Figure 19. JRC-EU-TIMES result: use of biomass resources (PJ)

7.3 Technology investments

The technology market reports and cross-sectorial report zoom into the details of investments and technology market deployment. This chapter gives an overview of the cumulative investments in key Low Carbon Energy Technologies from today up to 2050.

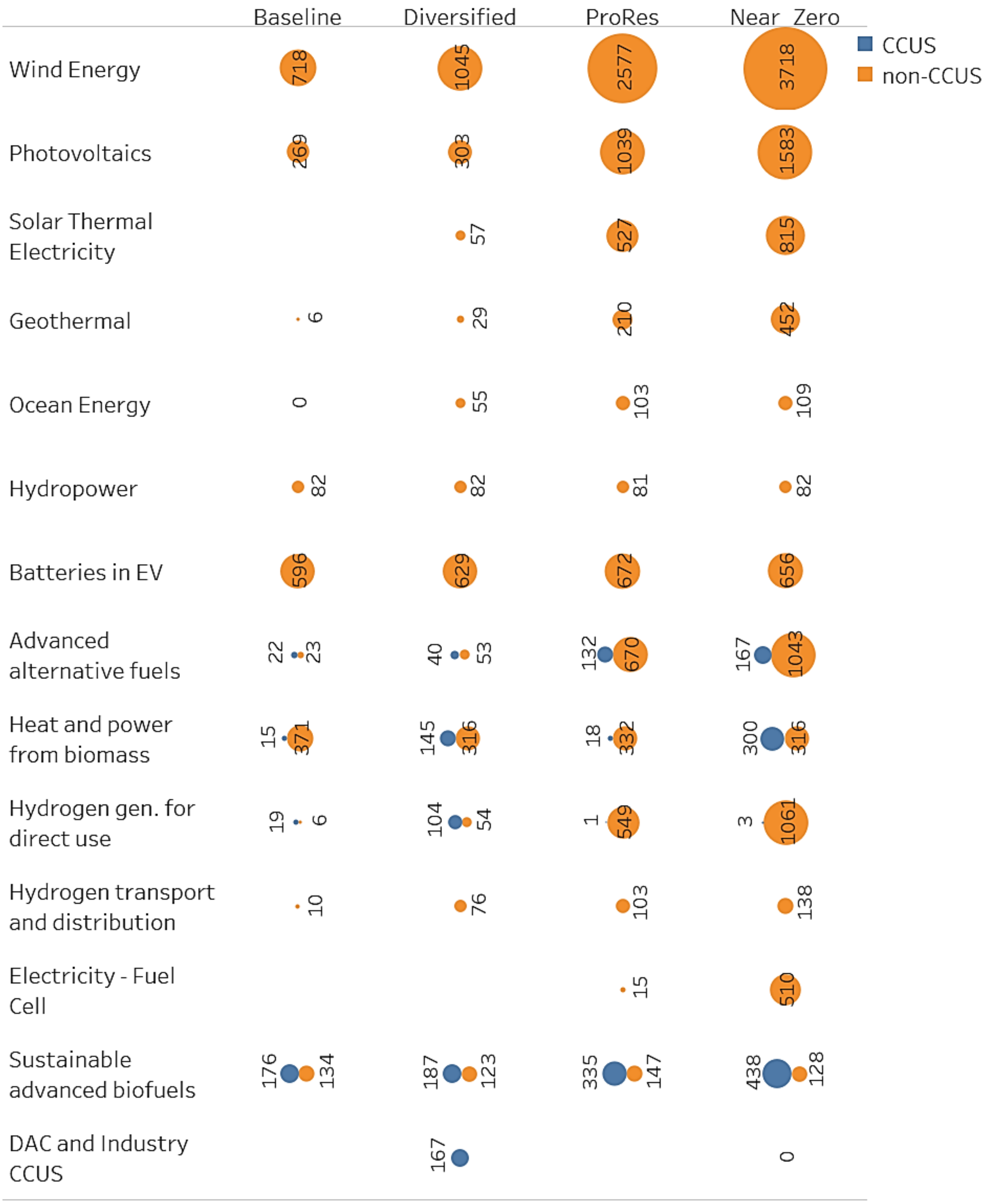

Figure 20. JRC-EU-TIMES result: cumulative investments in key Low Carbon Energy Technologies from today up to 2050 (BEUR)

- Already in the baseline, wind and solar alone make up almost 50% of investments made into new power generation capacities, with nuclear power plants accounting for 40% (not on the graph). For wind, it is equivalent to a continuation of the current market, EUR 22.3 billion in 2017[5]. For PV, the cumulative numbers seems small, especially when comparing across scenarios. However the market would still rapidly increase to EUR 12 billion by 2030 in the baseline. Beyond 2030, the PV market decreases from reaching a certain saturation level as described in 6.1 and from falling CAPEX costs.
- In the Diversified scenario, there are investments in both renewable and CCUS related technologies. For some CCUS technologies such as power plants the full investment is included which is much higher than only the capturing cost so the investments are somewhat inflated. For biofuel production, the full cost is shown even though there are no additional costs because CO_2 is a by-product.
- In the ProRES scenario, investments are primarily in wind, solar and advanced alternative fuels. The market of advanced alternative fuels could become a very large market especially given that it doesn't exist today. The largest part of these investments is in electrolysers. Interestingly, in this scenario without the option to permanently store CO_2 under the ground, more than 400 Mton/year CO_2 is still reused, again as a by-product from biofuel generation. The main use of this CO_2 is the production of diesel/kerosene by combining hydrogen and CO_2.
- For a near zero carbon world, with an additional reduction of CO_2 of 15% (to -95%), 50% additional investments are required for many technologies.

7.4 Impact of technology learning.

The impact of the different sensitivities (technology learning, resources and policies) is included in each individual technology result when it has a relevant impact. Deliverable D2.6 on synergies will also include sensitivity results to underpin technology interdependencies. In this report we give a short overview of the most remarkable impacts of general technology learning.

Regarding the impact of the learning rate, we conclude that it can have remarkable impacts on technology costs and thus also on the total system cost. Technology deployment is however still more impacted by the boundaries of the global storyline rather than the technology cost. The differences within each scenario are in other words smaller than the differences between scenarios. This can be explained by the fact that, given any technology learning, remarkable amounts of solar and wind will have to be installed to decarbonize the energy system without nuclear and CCS. The corresponding level of investments that such scenario would entail are high and the main impact of improved learning rates would be to lower these costs. We also conclude that there can be contra-intuitive impacts of learning on technology deployment. When learning affects the technology characteristics of multiple technologies, some deployment levels will be higher but some will be lower, even if the cost of one particular technology decreased. Other technologies may have improved even more or the improvement has a larger impact on the system. One example is 2nd generation biofuel. The improvements of that technology reduce the need of electrofuels bringing down the overall power production, even when cheaper PV is available.

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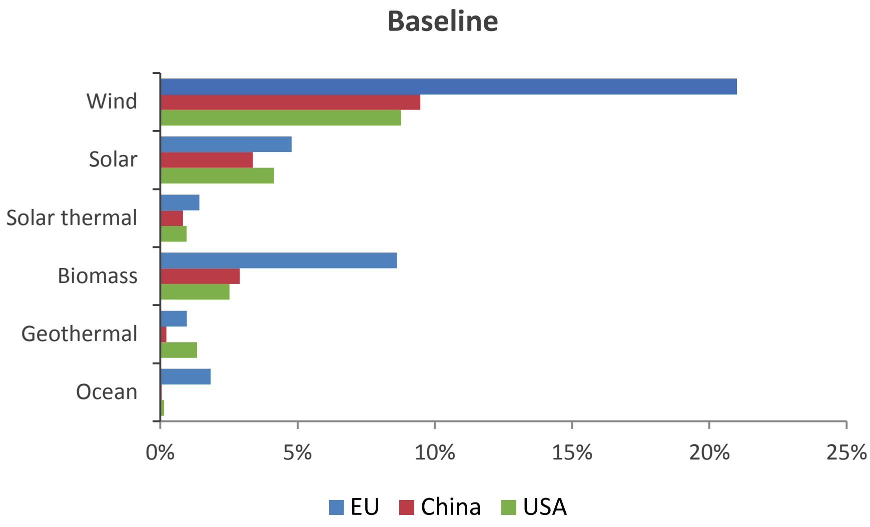
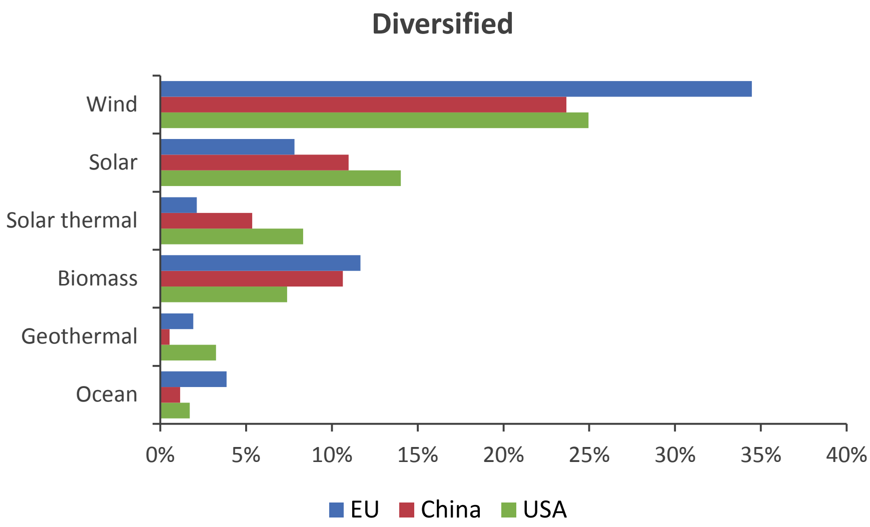
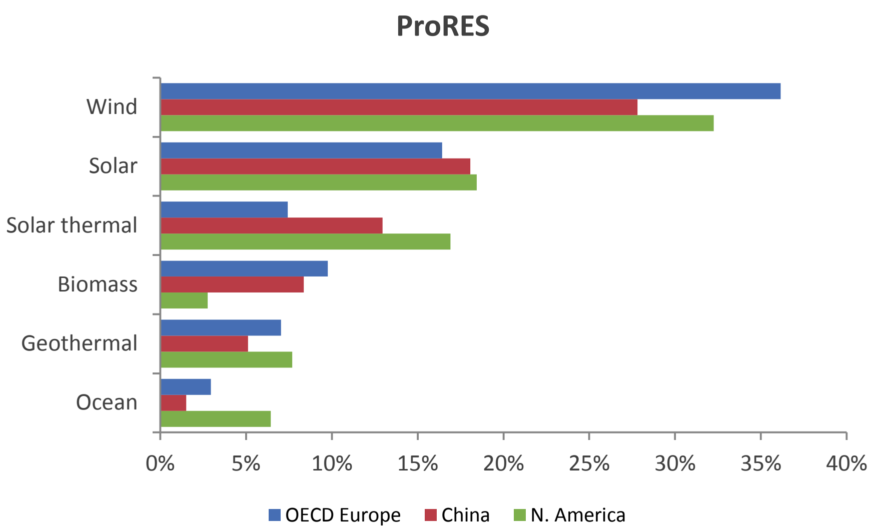
Annexes

Annex 1. Global RES-E shares in the three storylines in 2050

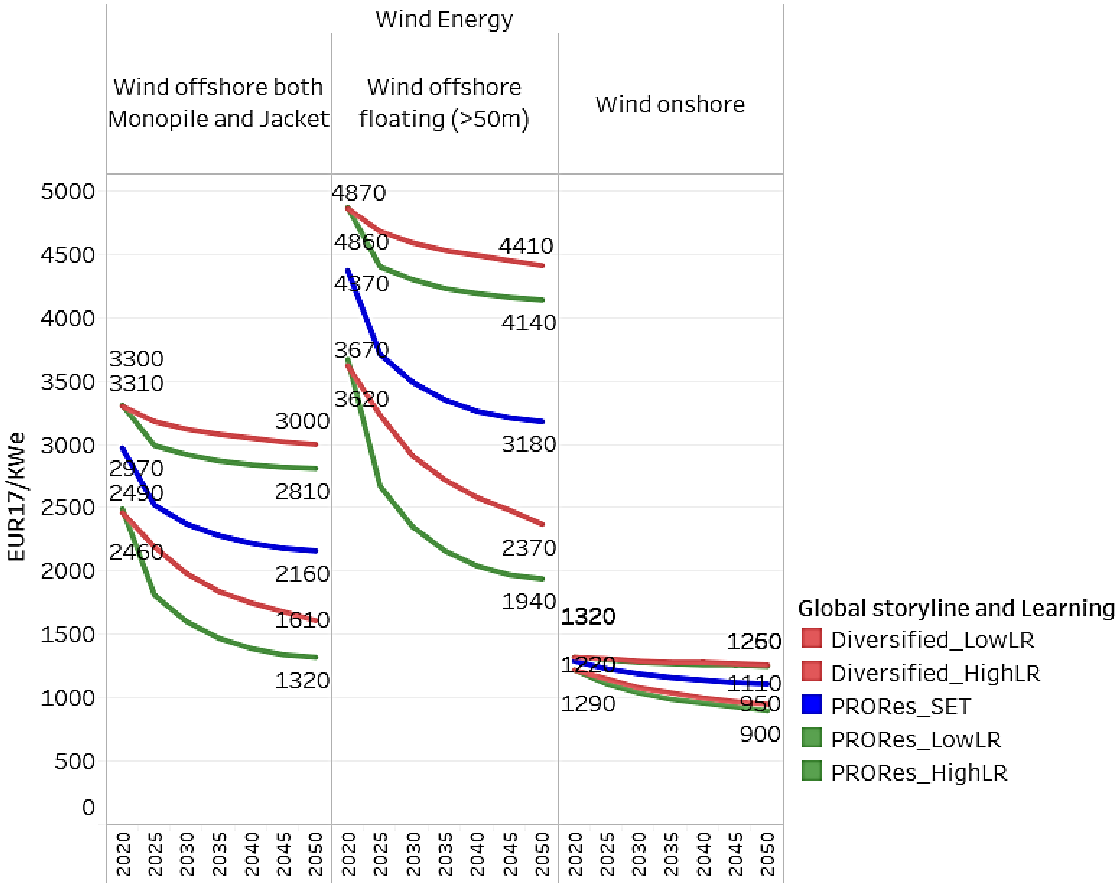


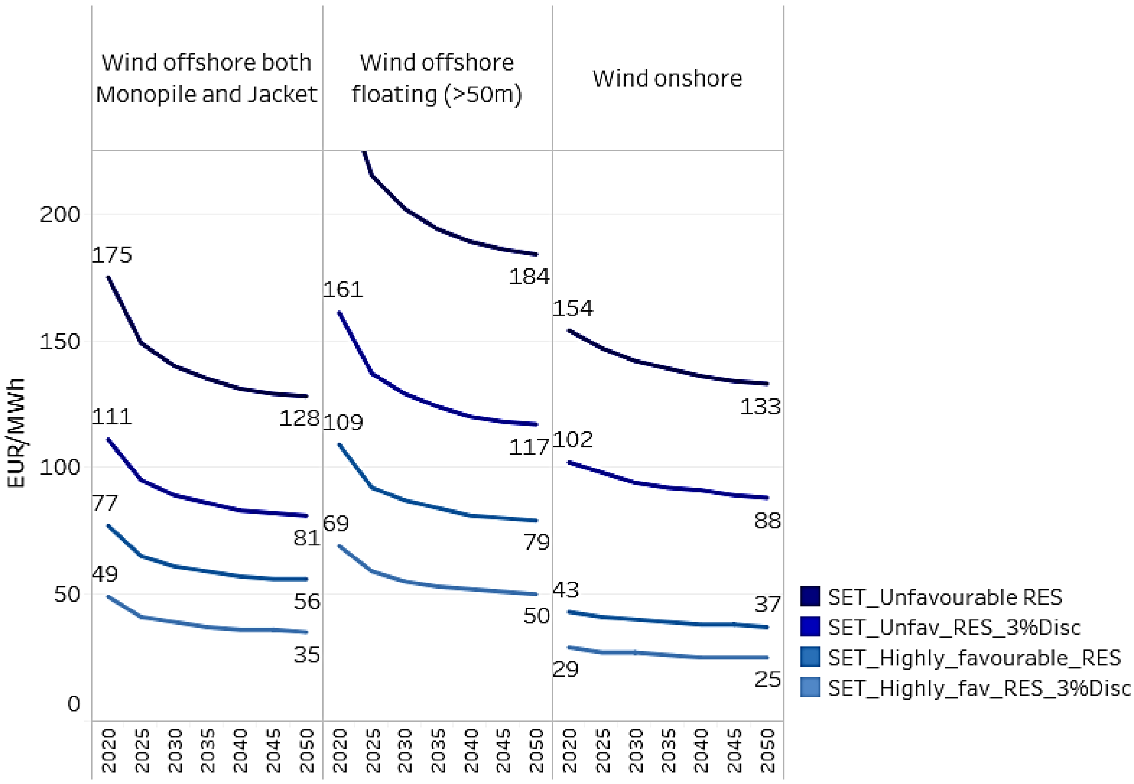




Annex 2. Assumptions cost wind (CAPEX and LCOE)

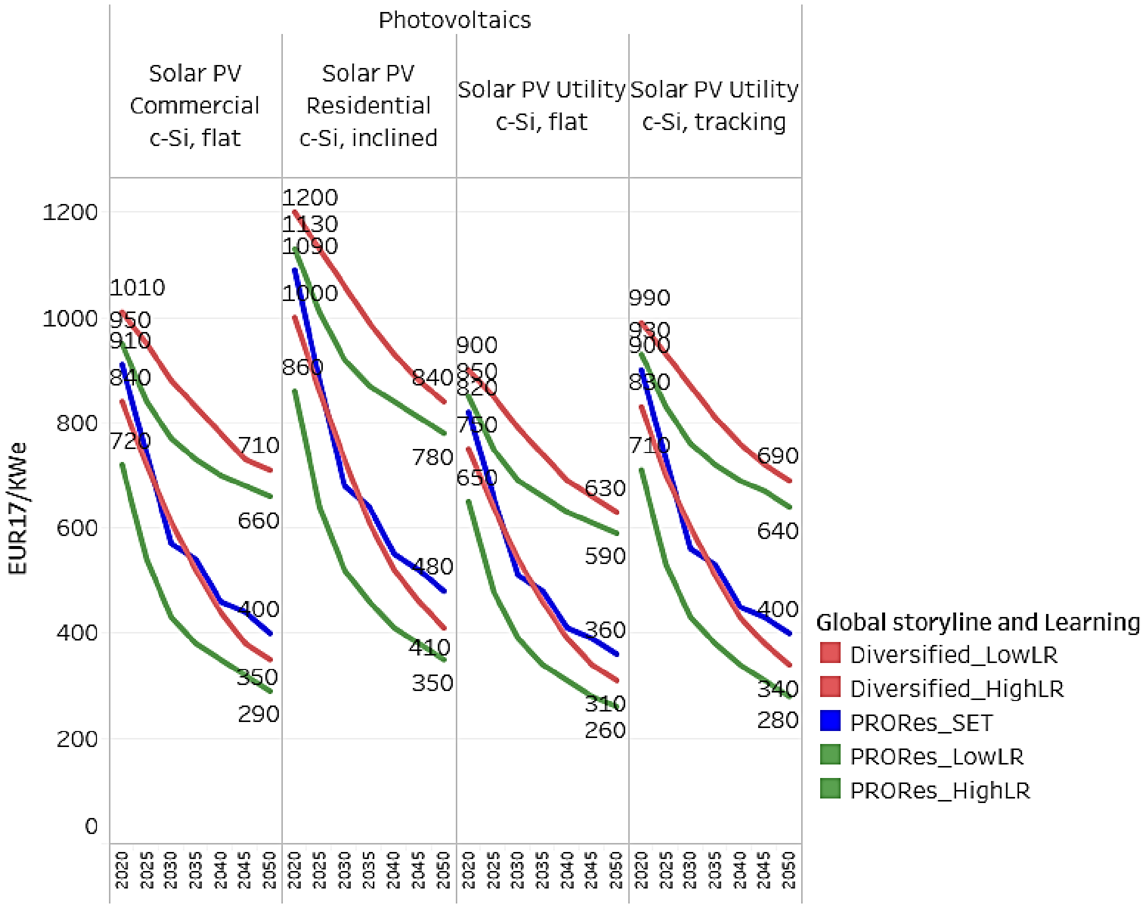
The Levelized Cost Of Electricity is calculated with a 9% discount rate (as in the model) and with a 3% (social) rate. Regions with highly favourable resources can be found in the North-East (for onshore especially in Ireland and parts of the UK). Regions with unfavourable resources are in the South-West of the EU (especially Italy and Croatia).

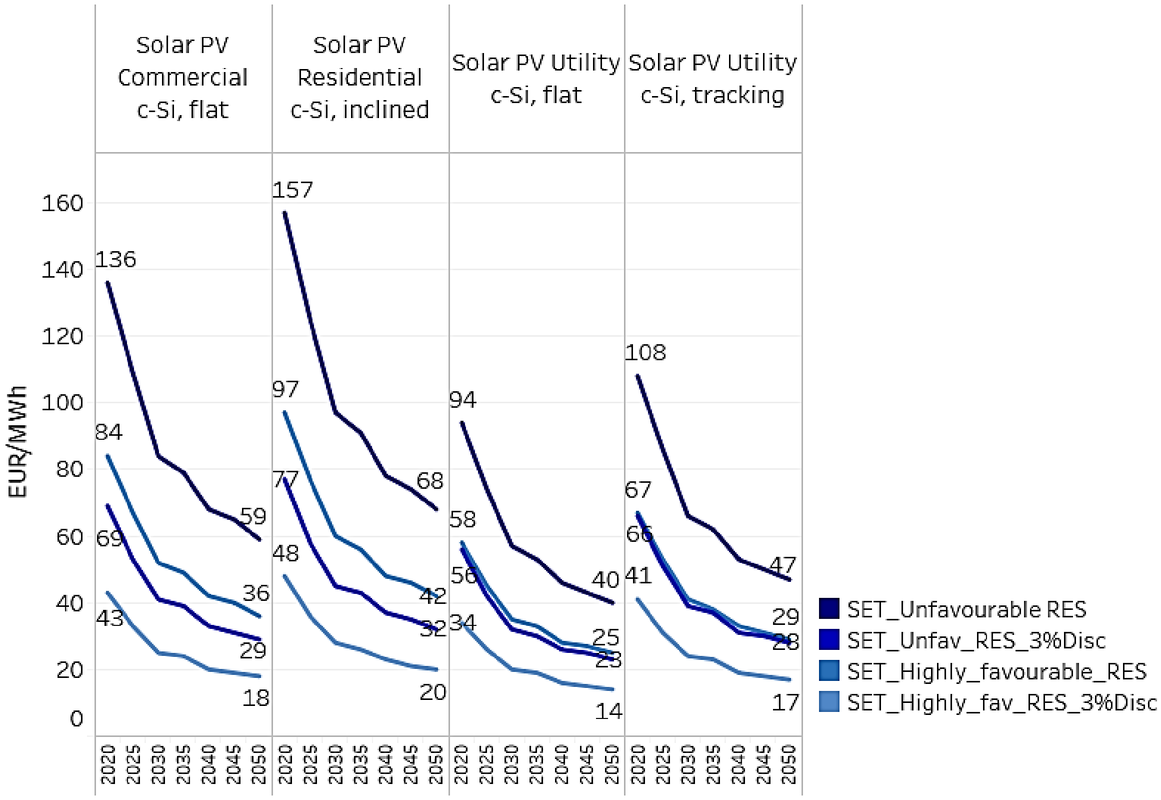




Annex 3. Assumptions cost Photovoltaic (CAPEX and LCOE)

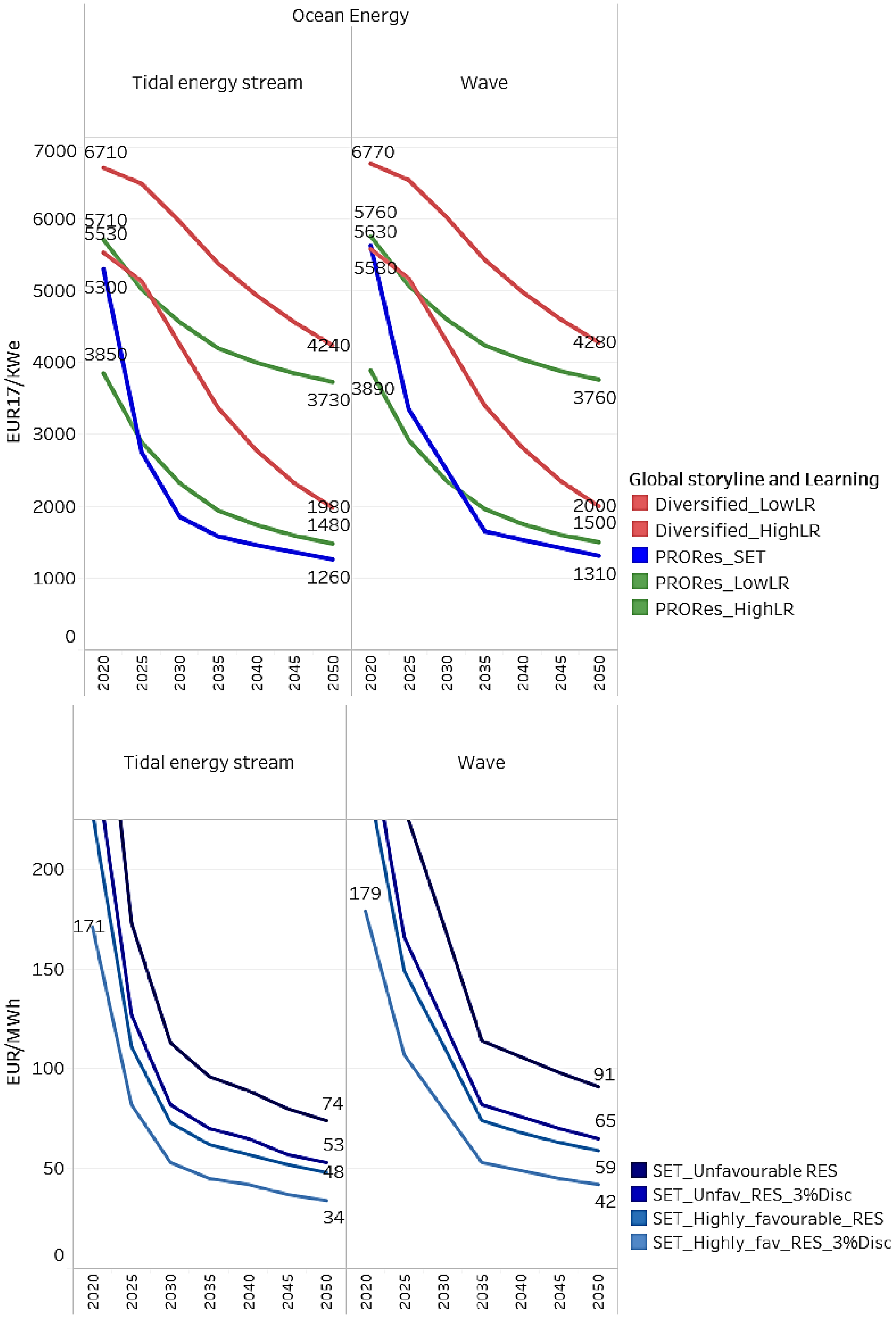
The Levelized Cost Of Electricity is calculated with a 9% discount rate (as in the model, residential however 12%) and with a 3% (social) rate. The LCOE in regions with highly favourable resources is 60% of the LCOE in regions with unfavourable conditions.





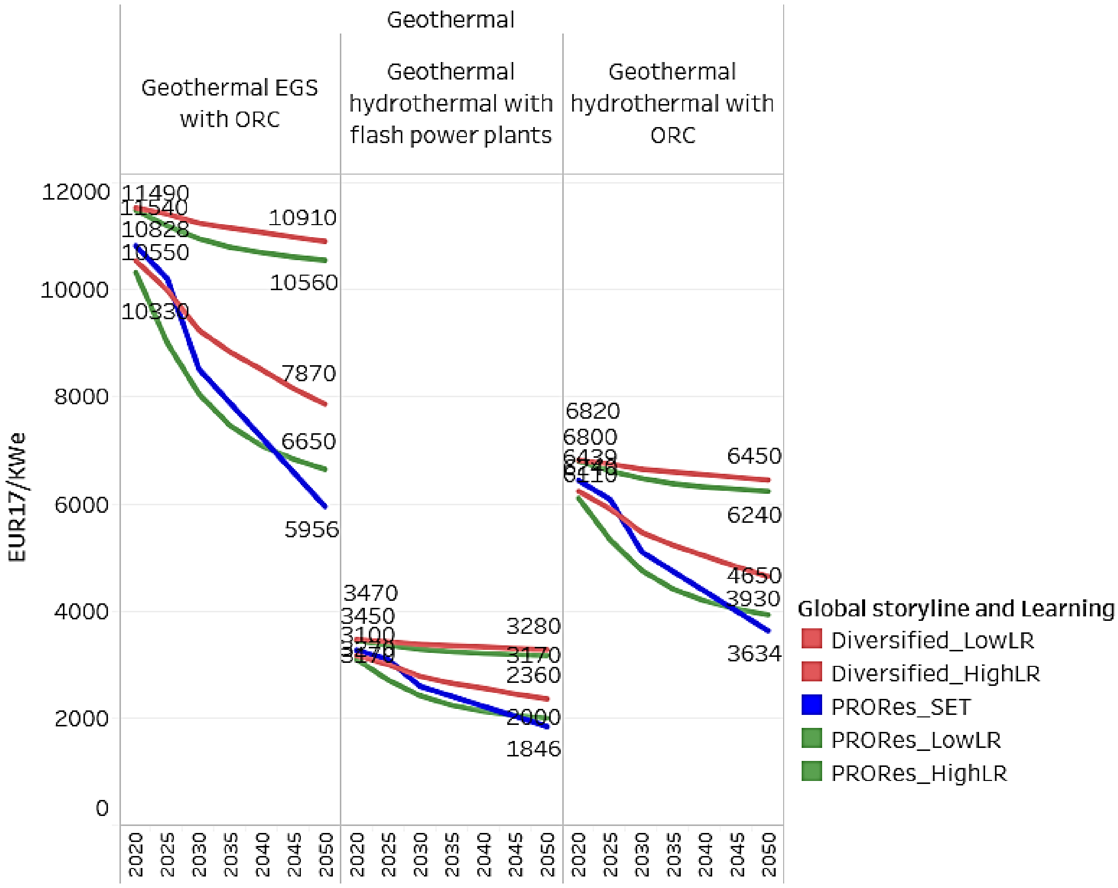
Annex 4. Assumptions cost ocean energy (CAPEX and LCOE)

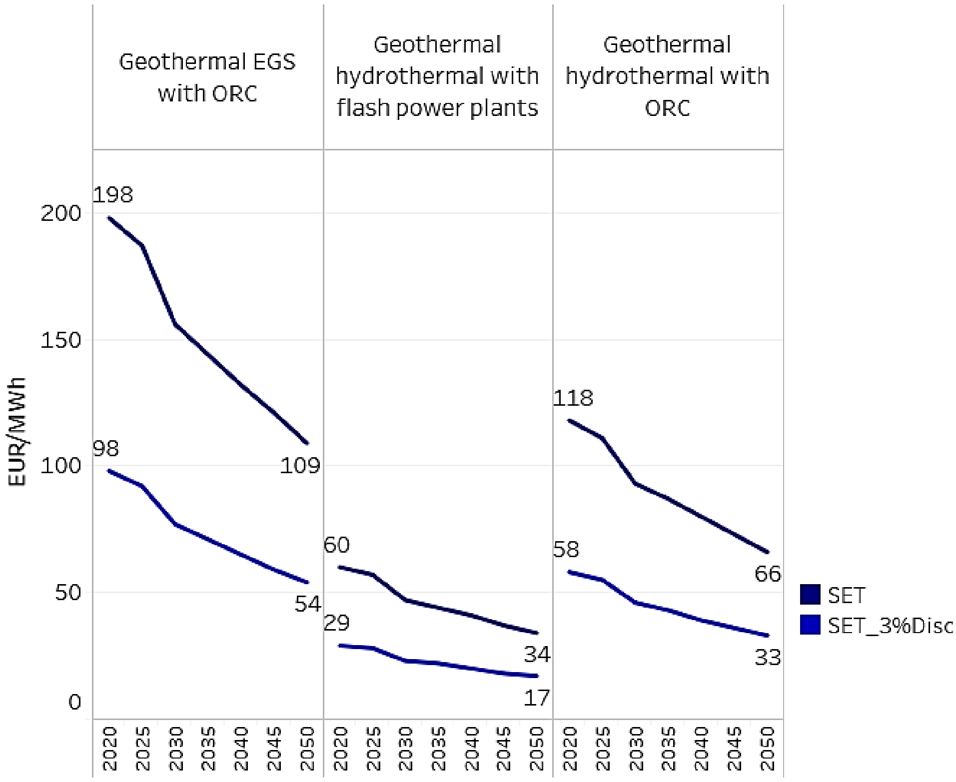
The Levelized Cost Of Electricity for ocean energy is calculated with a 9% discount rate (as in the model) and a 3% (social) discount rate.



Annex 5. Assumptions cost geothermal electricity (CAPEX and LCOE)

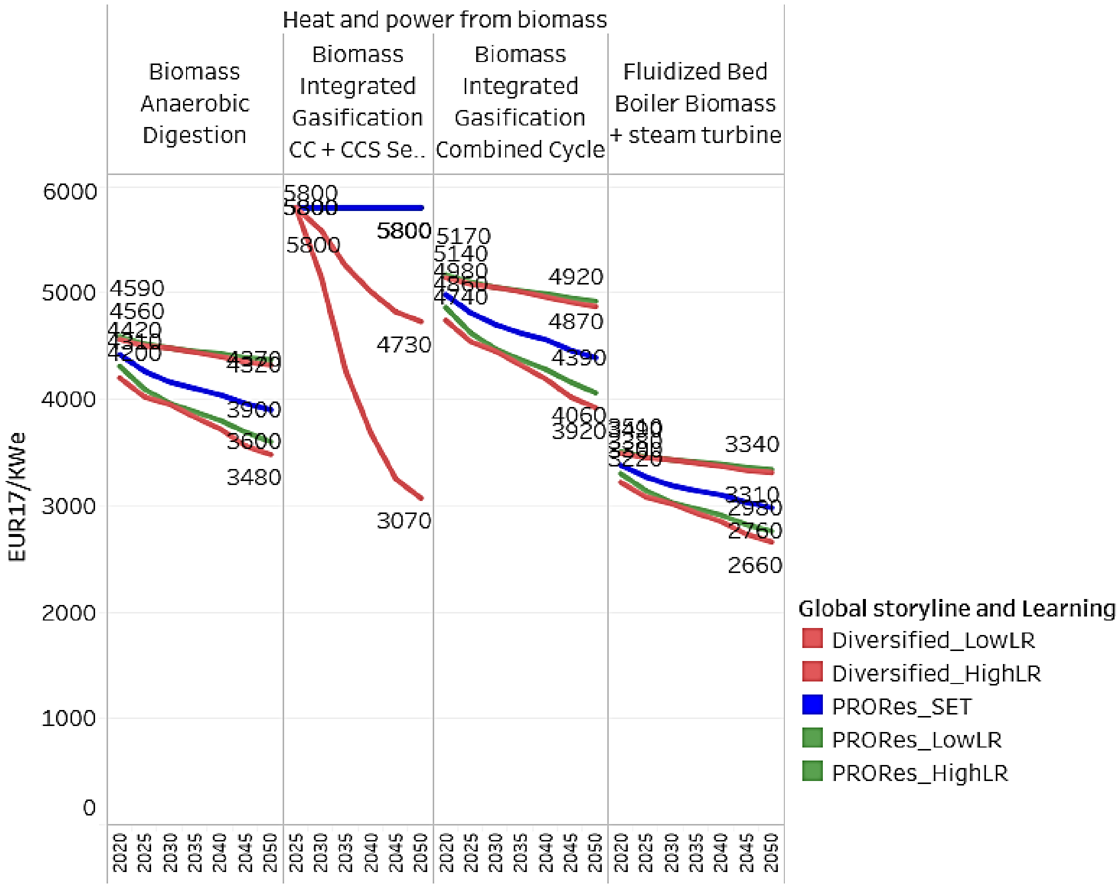
The Levelized Cost Of Electricity for geothermal is calculated with a 12% discount rate (as in the model) and with a 3% (social) rate.

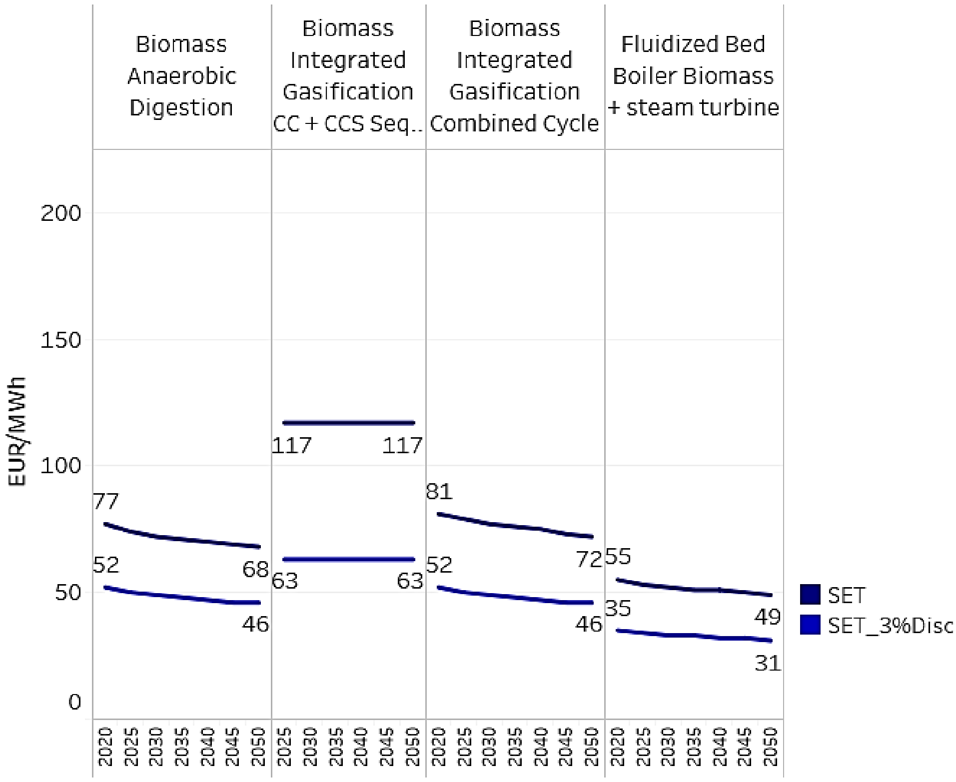




Annex 6. Assumptions cost heat and power from biomass (CAPEX and LCOE)

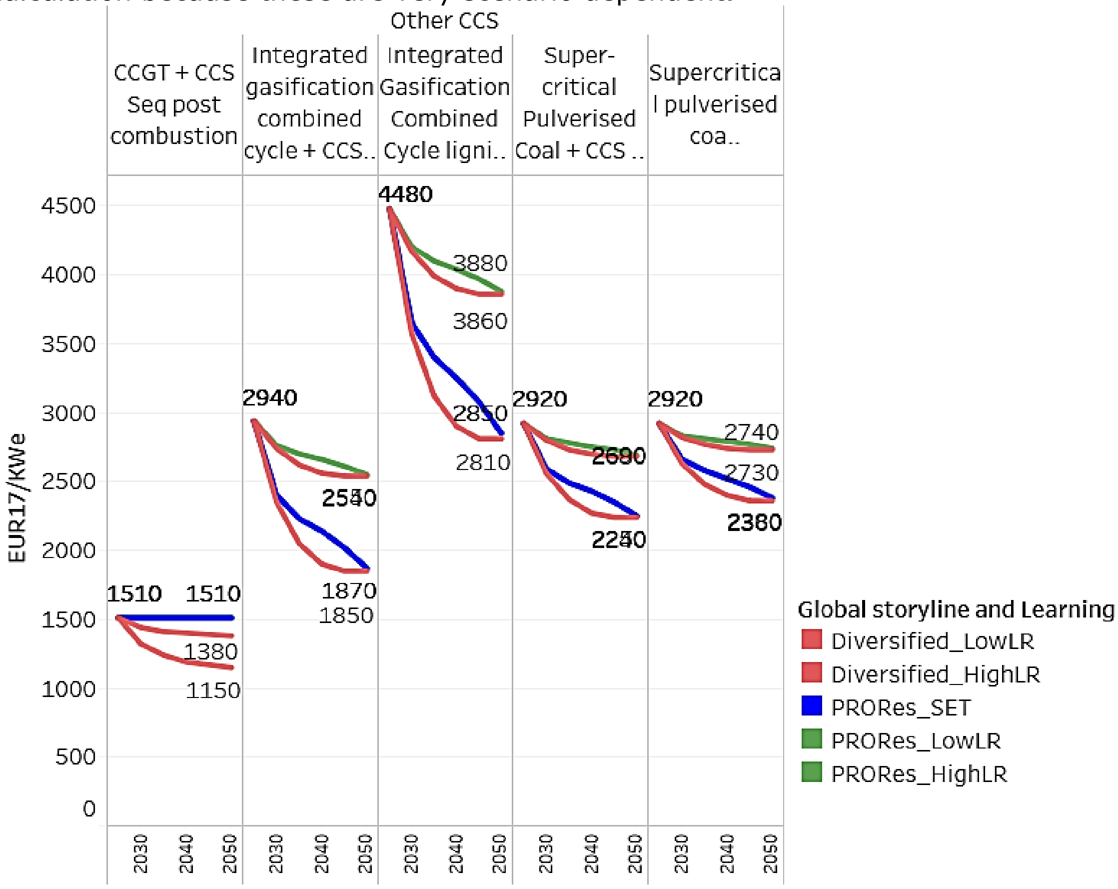
The Levelized Cost Of Electricity is calculated with a 9% discount rate except for CCS where 12% is used, as well as with a 3% (social) rate. No variable costs (fuel, CO_2 or other) are included in the calculation because these are very scenario dependent.

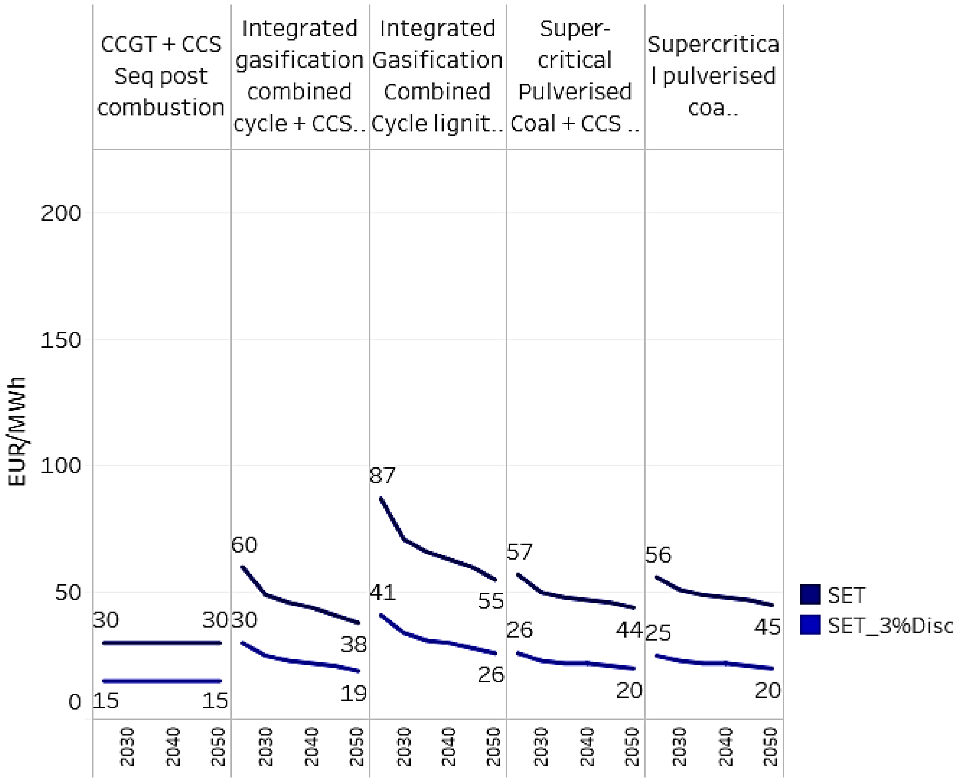




Annex 7. Assumptions cost power production with CCS (CAPEX and LCOE)

The Levelized Cost Of Electricity is calculated with a 12% discount (as in the model) and with a 3% (social) rate. No variable costs (fuel, CO_2 or other) are included in the calculation because these are very scenario dependent.





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