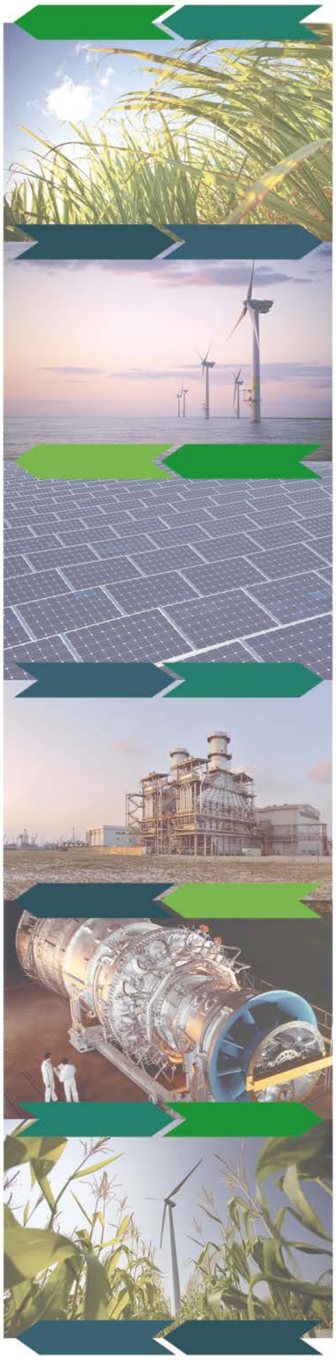
NAVIGATING THE ROADMAP FOR CLEAN, SECURE AND EFFICIENT ENERGY INNOVATION



Issue paper on

Diffusion rate of Renewable Electricity

An assessment of the optimal RES share under varying determinants

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SET-Nav
Strategic Energy Roadmap

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1 Introduction

This Issue Paper informs on a modelling case study within the SET-Nav project dedicated to analyse the optimal diffusion rate of renewable electricity generation within the European Union in the years up to 2050. The overall objective of the work package (WP7) in which this case study is embedded is to extend and apply the modelling capabilities of the project consortium for the analysis of the supply side of energy systems, with a particular focus on the electricity sector. In this context, enabling and improving interactions between the different models is a strong focus. In a first step, existing models are extended and case studies are conducted, shedding light on specific topics of interest and aiming to derive lessons learnt for the follow-up overarching model-based assessment by means of pathways/scenarios for the decarbonisation of the EU's energy sector.

This case study is dedicated to elaborate on **the diffusion of renewable electricity generation, aiming to gain insights on the suitable/optimal share renewables may take in Europe's future electricity supply.** Generally, renewable electricity generation (RES-E) is estimated to cover a high share of the future electricity demand in the EU. The possible diffusion of RES-E generation depends on the overall policy ambition in our combat against climate change, the relative costs of RES-E to its (low-carbon) alternatives, and the capability of the system to accommodate volatile generation.

In particular, we want to investigate how the diffusion rate changes as reaction to:

- **Technological learning / Cost trends:** Parameter changes in learning rates and the innovation system of renewable energy technologies. This part of the analysis has been contrasted with interim findings from our analysis within SET-Nav on technology innovation and policy implications (WP 3).
- **Market design / Flexibility provision:** The design and operation of electricity markets are broad topics of their own – within our analysis, we focus on some core issues that impact RES-E integration, including grid development, electricity market design, and sector coupling / demand-side response. The core question behind is how distinct trends within above-listed areas might affect the provision of flexibility required to accommodate variable generation. Here we build on respective assessments done within SET-Nav, e.g. the case study analysis of centralised and decentralised electricity supply and the infrastructure requirements imposed, but also on lessons learnt in other projects, e.g. the Intelligent Energy for Europe project towards2030-dialogue (www.towards2030.eu) where electricity market design trends have been subject of a thorough analysis performed.
- **Policy-related aspects / Policy ambition:** Energy and climate policy provides the guiding framework for all market actors in the energy sector. Policy decisions can lay the grounds for certain developments, ambitious policy targets may facilitate the uptake of certain energy technologies, and/or may hinder others. Without digging into details of how energy policy instruments are or should be designed, we take an umbrella view on how policy decisions may affect the optimal share of RES in the electricity sector. Three representative examples are taken up in our analysis:
    - how policy design may facilitate or hinder the uptake of decentral RES prosumers, exemplified for the case of decentral photovoltaics;
    - how the (pending) reform of the EU's Emission Trading Scheme (ETS) may impact future RES developments, and, finally,
    - how the overall policy ambition for renewables determines the required uptake of RES in the electricity sector, exemplified by the assumed overall target set for RES within the EU by 2030.

2 Method of approach

2.1 The applied modelling system: Green-X & Enertile

This analysis builds on modelling works undertaken by the use of TU Wien's Green-X model (cf. Box 1), closely linked to Fraunhofer ISI's Enertile model (cf. Box 2). More precisely, Green-X delivers a first picture of future RES developments under distinct energy policy trends and cost assumptions, indicating details on technology trends (investments, installed capacities and generation) and the geographical distribution of RES deployment as well as related costs (generation cost), expenditures (capital, operation and support expenditures) and benefits (avoided fossil fuels and related carbon emissions). For assessing the interplay between RES and the future electricity market, Green-X was complemented by its power-system companion, i.e. the Enertile model. Thanks to a higher intertemporal resolution than in the RES investment model Green-X, Enertile enables a deeper analysis of the merit order effect and related market values of the produced electricity of variable and dispatchable renewables and, therefore, can shed further light on the interplay between supply, demand and storage in the electricity sector.

Please note that for parts of the analysis, Enertile was replaced by TU Wien's HiREPS model, offering comparatively similar characteristics on power system modelling than Enertile but with additional features to assess impacts of electricity market design and system flexibility.[1]

Box 1: Brief characterization of the Green-X model

Green-X is an energy system model that offers a ***detailed representation of RES potentials and related technologies in Europe and in neighbouring countries****. It aims at indicating consequences of RES policy choices in a real-world energy policy context thanks to its comprehensive* ***incorporation of various energy policy instruments*** *including related design features. The model simulates technology-specific RES deployment by country on a yearly basis, in the time span up to 2050, taking into account the impact of dedicated support schemes as well as economic and non-economic framework conditions (e.g. regulatory and societal constraints). Moreover, the model allows for an appropriate representation of financing conditions and of the related impact on investor's risk. This, in turn, allows conducting in-depth analyses of future RES deployment and corresponding costs, expenditures and benefits arising from the preconditioned policy choices on country, sector and technology level.*

Box 2: Brief characterization of the Enertile model

Enertile is an energy system optimization model developed at the Fraunhofer Institute for System and Innovation Research ISI. The model focuses on the power sector, but also covers the interdependencies with other sectors, especially heating &cooling and the transport sector. It is used mostly for long-term scenario studies and is explicitly designed to depict the challenges and opportunities of increasing shares of renewable energies.

A major advantage of the model is its ***high technical and temporal resolution*** *– i.e. the model features a full hourly resolution: In each analysed year, 8,760 hours are covered. Since real weather data is applied, the interdependencies between weather regions and renewable technologies are implicitly included.*

Moreover, Enertile allows for a ***full optimization of the investments into all major infrastructures of the power sector*** [2]*, including conventional power generation, combined-heat-and-power (CHP), renewable power technologies, cross-border transmission grids, and flexibility options such as demand-*

[1] TU Wien's HiREPS model can build here on already established linkages between electricity and heating & cooling as well as transport, as analysed in the course of the Towards2030-dialogue project (cf. Resch et al, 2017). Such a model extension will be undertaken in a more detailed manner within Enertile in the course of this project.

[2] For the purpose of this case study, investments in RES technologies were taken from Green-X modelling. Thus, Enertile focussed on modelling complementary investment needs as well as power plant dispatch.

side-management (DSM) and power-to-heat storage technologies. The model chooses the optimal portfolio of technologies while determining the utilization of these for all hours of each analysed year.

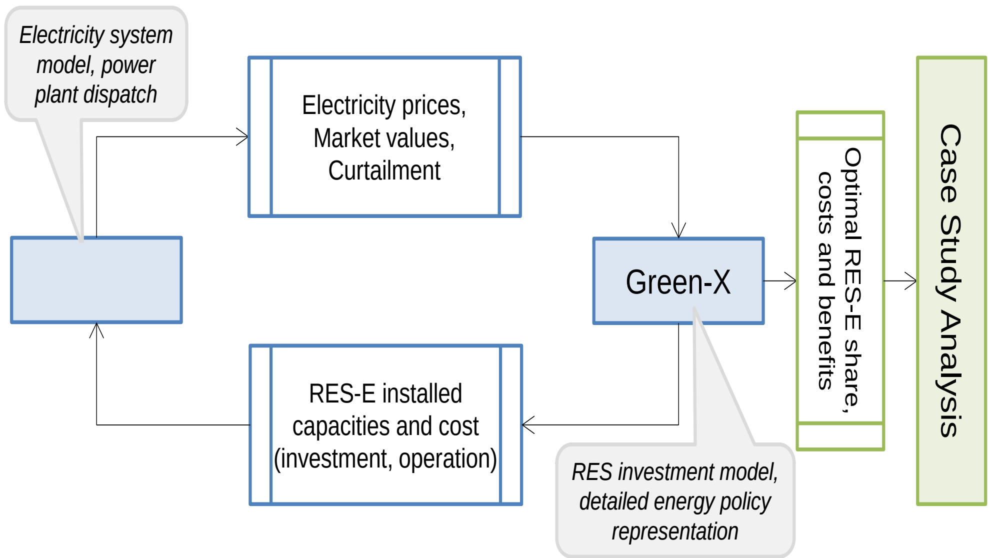

Figure 1: Model coupling between Enertile (left) and Green-X (right) for a detailed assessment of RES developments in the electricity sector

Figure 1 gives an overview on the interplay of both models. Both models are operated with the same set of general input parameters, however in different spatial and temporal resolution. Green-X delivers a first picture of renewables deployment and related costs, expenditures and benefits by country on a yearly basis (2010 to 2050). The output of Green-X in terms of country- and technology-specific RES capacities and generation in the electricity sector for selected years (2020, 2030 and 2050) serves as input for the power-system analysis done with Enertile. Subsequently, the Enertile model analyses the interplay between supply, demand, and storage in the electricity sector on an hourly basis for the given years. The output of Enertile is then fed back into the RES investment model Green-X. In particular, the feedback comprises the amount of RES that can be integrated into the grids, the electricity prices, and corresponding market revenues (i.e. market values of the electricity produced by variable and dispatchable RES-E) of all assessed RES-E technologies for each assessed country.

2.2 Overview on key assumptions and assessed scenarios

Aiming at an analysis of the optimal diffusion rate of renewable electricity in dependence of key determinants, a set of seven different scenarios has been assessed so far. An overview on their definition is given in Table 1, providing a key characterisation of the individual scenarios and listing key input parameters and assumptions. From a topical viewpoint, we distinguish between three topical areas: technological learning / cost trends, market design / flexibility provision, and policy-related aspects.[3]

[3] The scenario(s) assessed under these topical areas show how the optimal diffusion rate / share of RES-E changes in comparison to the reference scenario (of aiming for 27% RES by 2030 under default assumptions).

Table 1: Overview on assessed scenarios

Scenario acronym	27% RES	27% RES - low learning	27% RES - high learning	27% RES - trend market design	27% RES - no prioritisation of decentral PV	27% RES - high carbon prices	30% RES - strong EE
Topical area		Technological learning / Cost trends		Market design / Flexibility provision	Policy-related aspects / Policy ambition		
Characterisation	Default (reference) scenario	Low technological learning of key technologies	High technological learning of key technologies	Trend market design (non-optimal framework conditions for RES integrat.)	No prioritisation (higher retail value) of decentral RES (PV)	High carbon prices (major ETS reform)	Strong policy ambition for RES and EE by 2030
Energy demand trend	**27% EE* by 2030** (PRIMES euco27)	**27% EE by 2030** (PRIMES euco27)	**27% EE by 2030** (PRIMES euco27)	**27% EE by 2030** (PRIMES euco27)	**27% EE by 2030** (PRIMES euco27)	**27% EE by 2030** (PRIMES euco27)	**30% EE by 2030** (PRIMES euco30)
Fossil energy price trend	**Default** (PRIMES 2016)	**Default** (PRIMES 2016)	**Default** (PRIMES 2016)	**Default** (PRIMES 2016)	**Default** (PRIMES 2016)	**Default** (PRIMES 2016)	**Default** (PRIMES 2016)
Carbon price trend	**Default** (PRIMES reference)	**Default** (PRIMES reference)	**Default** (PRIMES reference)	**Default** (PRIMES reference)	**Default** (PRIMES reference)	**High** (PRIMES euco27)	**Default** (PRIMES reference)
Market design / Flexibility provision	**Optimal** (grid extension, energy only markets, demand response)	**Optimal** (grid extension, energy only markets, demand response)	**Optimal** (grid extension, energy only markets, demand response)	**Trend** (delayed grid ext., capacity markets, no demand response)	**Optimal** (grid extension, energy only markets, demand response)	**Optimal** (grid extension, energy only markets, demand response)	**Optimal** (grid extension, energy only markets, demand response)
RES ambition	at least **27% by 2030** (and beyond)	at least **27% by 2030** (and beyond)	at least **27% by 2030** (and beyond)	at least **27% by 2030** (and beyond)	at least **27% by 2030** (and beyond)	at least **27% by 2030** (and beyond)	at least **30% by 2030** (and beyond)
RES policy concept	**Least cost** (support expenditures)	**Least cost** (support expenditures)	**Least cost** (support expenditures)	**Least cost** (support expenditures)	**Least cost** (support expenditures)	**Least cost** (support expenditures)	**Least cost** (support expenditures)

*Abbreviation: EE … energy efficiency

Next we introduce the set of common key input parameter and assumptions.

2.2.1 General input parameter and assumptions

In order to ensure maximum consistency with existing EU scenarios and projections the key input parameters of the scenarios presented in this report are derived from PRIMES modelling and from the Green-X database (www.green-x.at) with respect to the potentials and cost of RES technologies. As indicated in Table 1 (above), PRIMES comes into play for **energy demand developments** as well as **fossil energy and carbon price trends**. The specific PRIMES scenarios used are the latest publicly available reference scenario (European Commission, 2016f) and the climate mitigation scenarios PRIMES euco27 and PRIMES euco30 that build on the targeted use of renewables (i.e. 27% RES by 2030) and an enhanced use of energy efficiency (EE) compared to reference conditions – i.e. 27% (euco27) or 30% EE (euco30) by 2030, respectively. Please note that all PRIMES scenarios are intensively discussed in the EC's winter package, cf. the Impact assessment of the recast RED (SWD (2016) 410 final) (European Commission, 2016).

With respect to the underlying **policy concept and ambition level for RES and energy efficiency,** the following assumptions are taken for the assessed scenarios:

- *A common policy framework until 2020:* All scenarios build on common ground for the near future, i.e. the years up to 2020. Here, a strengthening of national RES policies is presumed, serving to meet the given 2020 RES targets. Each country uses national (in most cases technology-specific) support schemes in the electricity sector to meet its own 2020 RES target, complemented by RES cooperation between Member States in the case of insufficient or comparatively expensive domestic renewable sources. Please note that support levels are tailored to the national needs, in other words, they are generally based on the technology specific generation costs at country level.
- *A "least-cost" approach for RES post 2020:* For renewables, the default ambition level is generally set at 27% - i.e. ***achieving a RES share in gross final energy demand in size of at least 27% by 2030 and beyond***. [4] Conceptually, the scenarios follow a simplified policy concept for renewables: The underlying policy concept for incentivising RES can be characterised as a "least-cost" approach, enhancing an efficient use of RES for meeting the 2030 EU RES target in a cost-effective manner as outlined in Box 3.

  Please note that *this "virtual" policy concept matches perfectly with the objective of this case study*. Thus, the ***RES policy approach taken in modelling allows for deriving the optimal RES-E share under given assumptions from a European least (policy) cost perspective*** – i.e. allowing for minimising support expenditures required for meeting a certain overall RES target by 2030 and beyond. Thus, the undertaken least cost allocation of the RES efforts to the available RES technologies across all energy sectors (electricity, heat, transport fuels) and countries (EU28 Member States) delivers an optimal RES deployment under given constraints.
- Concerning the role of *energy efficiency* a moderate ambition level is presumed – i.e. in accordance with the PRIMES euco27 scenario, gross final energy demand is reduced by 27% in 2030 compared to baseline conditions.

Box 3: A least-cost approach to allocate investments in RES technologies post 2020

The selection of RES technologies in the period post 2020 in all assessed cases within this exercise follows a least-cost approach, meaning that all additionally required future RES technology options are ranked in a merit-order, and it is left to the economic viability which options are chosen for meeting the presumed 2030 RES target. In other words, a least-cost approach is used to determine investments in RES technologies post 2020 across the EU. This allows for a full reflection of competition across technologies and countries (incorporating well also differences in financing conditions etc.) from a European perspective. Support levels and related expenditures follow then the marginal pricing concept where the marginal technology option determines the support level (like in the ETS or in a quota/certificate trading regime, or similar to the concept of liberalised electricity markets).

[4] The overall RES target as presumed for 2030 – i.e. as default (at least) 27% RES share in gross final energy demand – is maintained in modelling as minimum target also for the period post 2030 (until 2050). Draft results show, however, that in all assessed scenarios the minimum target level is over fulfilled, meaning that RES deployment is then well above 27% in the years up to 2050.

3 Results of the model-based analysis

3.1 RES deployment at the aggregated level

We start with an analysis of RES deployment according to the Green-X scenarios conducted within this case study. Since Green-X modelling builds on PRIMES scenarios that have been developed for and are discussed in the Impact Assessment accompanying the Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (COM(2016) 767 final), we involve these as well. In this context, Figure 2 below shows the development of the RES share in gross final energy demand throughout the period 2015 to 2030 in the EU28 according to the assessed Green-X scenario. As reference for 2030 also the shares in the PRIMES scenarios (i.e. PRIMES reference as of 2016 as well as PRIMES euco27and euco30 – the EU's central scenarios related to RES use post 2020) are indicated. Noticeably, an alignment to PRIMES results could be achieved at the aggregated level (i.e. on total RES deployment, EU28) for the policy track aiming for a (minimum) RES share of 27% by 2030.

A closer look at the impact of assessed determinants concerning the optimal diffusion of RES electricity, done by conducting a set of sensitivity scenarios under the same RES policy concept / ambition (i.e. the 2030 target of (at least) 27% RES by 2030 under a least-cost policy framework), shows only a small changes at the aggregated level (i.e. on the overall RES share). As shown in Figure 2 or, specifically for 2030, in Figure 3 (left), in the case of high learning of selected key RES-E technologies (i.e. wind and photovoltaics) (i.e. scenario "27% RES – high learning") the minimum share would be succeeded – but only by 0.1 percentage points. A more pronounced impact arises in the case of a proactive ETS-reform, leading presumably to high carbon prices, specifically in the long term close to 2050 (i.e. scenario "27% RES – high carbon prices"): here overall RES deployment increases to a 27.4% RES share in gross final energy demand by 2030. The upper boundary of RES deployment within this modelling exam is set by the scenario "30% RES – strong EE": the 2030 RES share increase to 30% by 2030 because of the higher imposed RES policy ambition – i.e. a minimum RES target of 30% instead of 27% is imposed under this scenario.

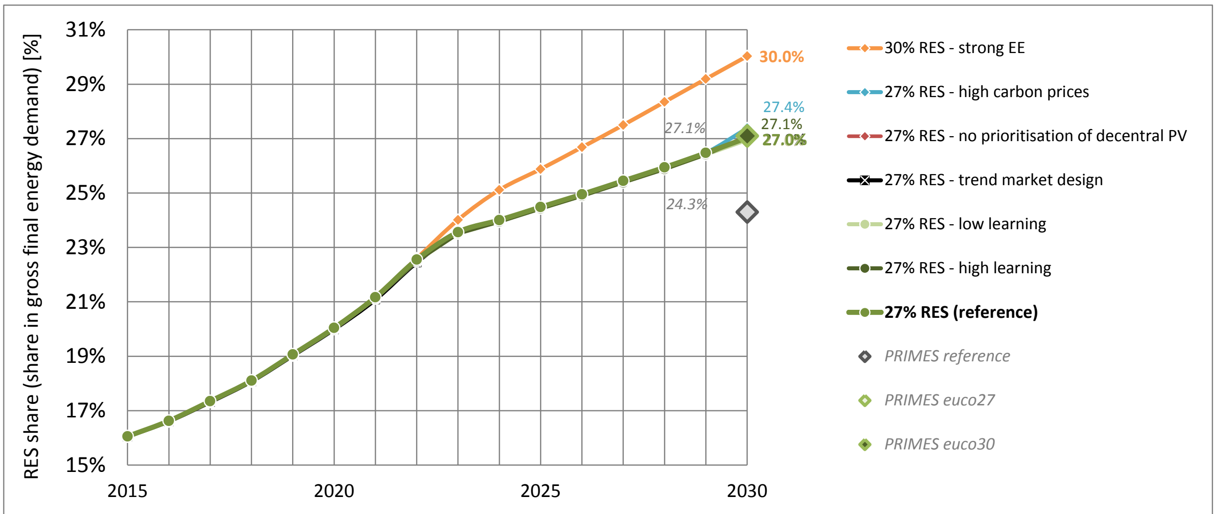

Figure 2: RES deployment in relative terms (i.e. as share in gross final energy demand) over time in the EU 28 for assessed scenarios

The right-hand side of Figure 3 provides interesting insights on how RES deployment in relative terms translates into absolute energy volumes – i.e. Mtoe or TWh of energy that need to be produced from renewable sources by 2030. Apparently, with stronger ambition related to energy efficiency the need for deploying renewables declines. As a consequence, only a 6% higher amount of renewables is needed to reach a 30% RES by 2030 under strong energy efficiency instead of striving for 27% RES in the case of moderate energy efficiency, cf. scenario "30% RES – strong EE" with e.g. scenario "27% RES (reference)".[5] In general terms, RES electricity is expected to provide the strongest contribution to overall RES target achievement: already by 2020 around 1,300 TWh, corresponding to ca. 48% of total RES generation in 2020, is expected to stem from RES in the electricity sector. According to the modelling conducted, reflecting a least-cost allocation of the 2030 RES target, RES-E generation would then increase further until 2030, reaching 1,713 TWh in 2030, corresponding to a share of 50.6% in total RES use, in a scenario that reflects a continuation of current trends of electricity market design (i.e. scenario "27% RES – trend market design", with delayed grid development, capacity markets as common market design, and no demand response). These scenario settings can be classified as least beneficial circumstances among the analysed cases. At the positive end, scenario "27% RES – high carbon prices" indicates an increase of RES-E generation up to 1,801 TWh until 2030, corresponding to a share of 52.5% in total RES use by then. With a range from 1,412 to 1,446 TWh RES in heating & cooling is expected to deliver the second largest contribution, achieving a share of 41.1%-42.8% in total RES use, depending on the assessed underlying circumstances. A comparatively stable deployment of biofuels in transport is observable, driven by the moderate sectoral target imposed for RES in transport (and in consequence causing slight deviations from a purified cross-sectoral least cost allocation of RES use)

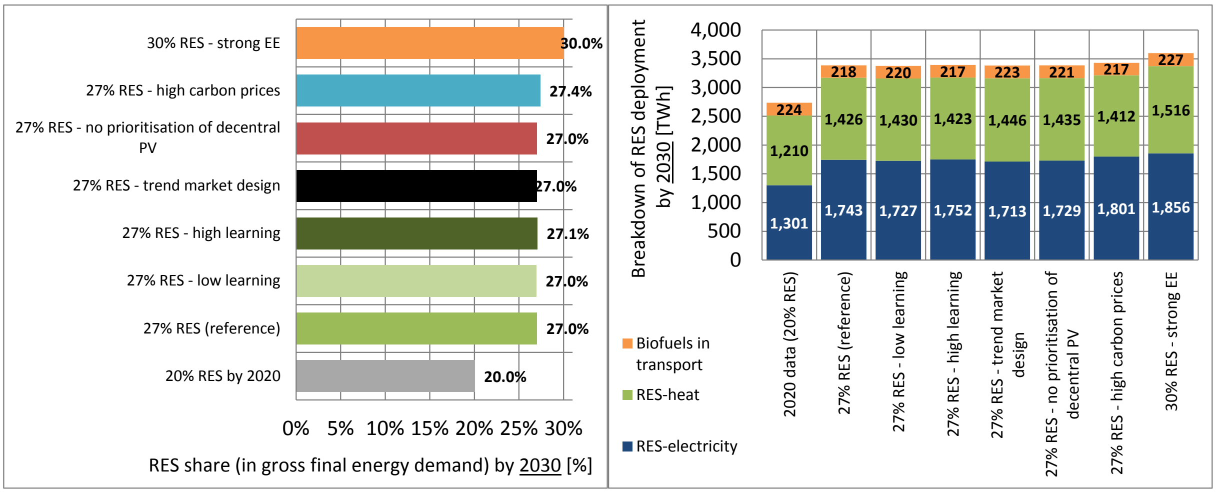

Figure 3: 2030 RES deployment: RES share in gross final energy demand (left) and sectorial decomposition of RES use in absolute terms (right) in the EU 28 according to assessed scenarios

3.2 RES developments in the electricity sector

The optimal RES-E share in dependence of assessed determinants

Next we take a closer look at RES in the electricity sector, aiming to clarify the central question underlying this modelling case: how is the optimal RES-E share under a cross-sectorial least-cost allocation of RES use affected by assessed determinants? Similar to Figure 2, Figure 4 provides an illustration of the required RES deployment in the electricity sector at EU28 level in the period up to 2030 in relative terms, depicting the expected development of the RES share in gross electricity demand according to the assessed

[5] An increase of the targeted RES share from 27% to 30% (as share in gross final energy demand) corresponds to an increase by 11% of RES use in absolute terms – if the underlying demand would be the same. As a consequence of the at the same time imposed stronger efficiency (i.e. increasing the EE target from 27% to 30%) the correspondingly required RES use in absolute terms increases however only by 6%.

modelling cases. Striving for 27% RES by 2030 implies to achieve a RES-E share around 50% at the same point time – if a least-cost policy approach is followed as conditioned in this exercise. Increasing the RES ambition to 30% by 2030 would for example lead to an increase of the RES-E share to around 55%. As discussed for total RES above, energy efficiency impacts the required RES-E deployment in absolute terms – i.e. the amount of energy stemming from renewable sources (cf. Figure 3 (right)).

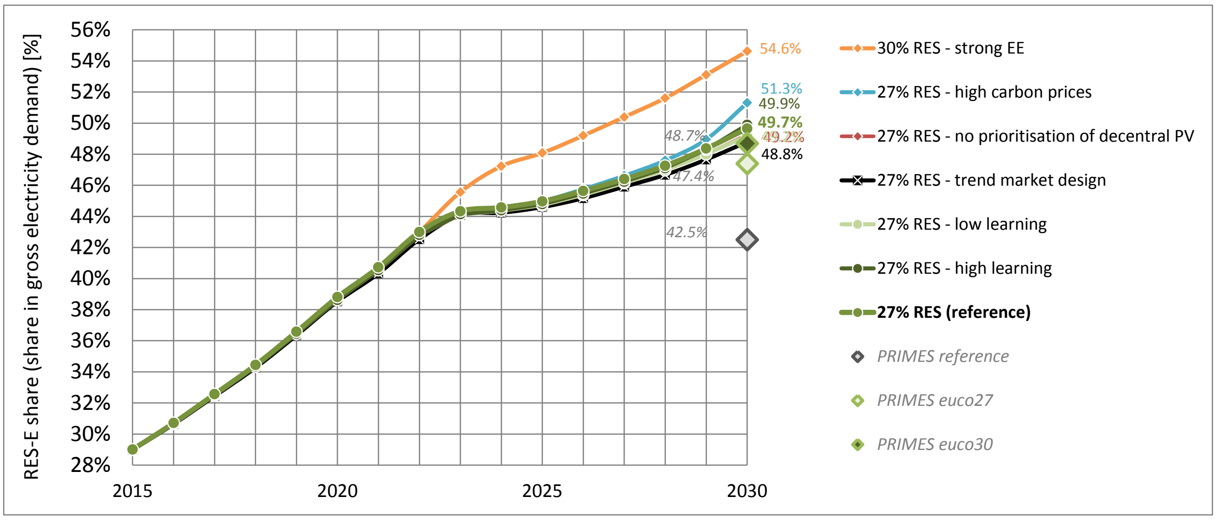

Figure 4: RES-E deployment in relative terms (i.e. as share in gross electricity demand) over time in the EU 28 for assessed scenarios

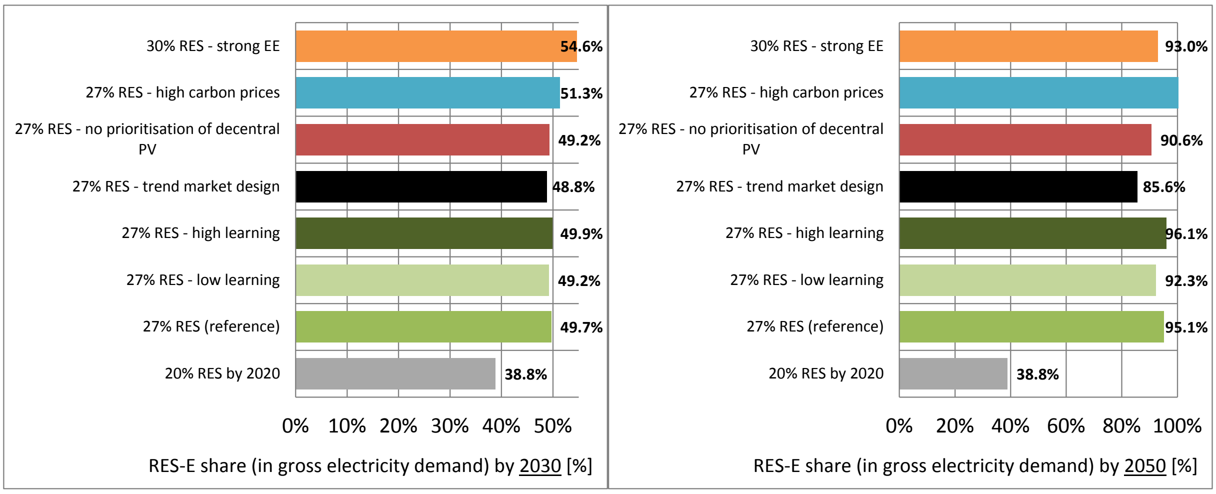

Figure 5: RES-E deployment 2030 and beyond: RES-E share in gross electricity demand by 2030 (left) and by 2050 (right) in the EU 28 according to assessed scenarios

In accordance with the central question underlying this case study (i.e. elaborating on the optimal RES-E share in dependence of assessed determinants), Figure 5 takes ***a closer look at the resulting RES-E deployment by 2030 and beyond***. More precisely, this graph illustrates the resulting RES-E share in gross electricity demand by 2030 (left) for all assessed scenarios. The right-hand side of this graph provides also an outlook to 2050, indicating the expected RES-E share by that point in time.

Key results and findings derived from these depictions are:

- Under *default framework conditions* – i.e. moderate learning, optimal electricity market design, moderate carbon prices, and a RES policy framework that safeguard a minimum RES share of 27% RES by 2030 and beyond – as presumed in the reference scenario "27% RES" a RES-E share of 49.7% is reached in 2030. In the forthcoming years post 2030 RES-E deployment would then further increase because of expected ongoing improvements in economic viability, driven by technological progress of underlying technologies as well as by assumed increases in fossil fuel and carbon prices. In 2050 modelling indicates an impressive increase of the absolute and relative RES-E deployment, reaching a RES-E share in gross electricity demand of 95.1%.

- *Technological learning* has an impact on these developments as observable from the related scenarios where either a 20% (compared to default) lower (i.e. scenario "27% RES – low learning") or a 20% higher learning rate (i.e. scenario "27% RES – high learning") is assumed for key technologies like wind energy and photovoltaics. As a consequence of the comparatively limited time span until 2030, only a small impact on the resulting 2030 RES-E share is applicable: the default RES-E share decreases by 0.5 percentage points to 49.2% in the case of low learning, and it is expected to increase by 0.2 pp to 49.9% in the case of high learning. By 2050 effects are more pronounced: here low learning of wind and photovoltaics would cause a decline of the RES-E share by 2.8 pp (i.e. from 95.1% (reference) to 92.3% (scenario "27% - low learning"). In the contrary, in the case of high learning the resulting RES-E share would increase by 1 pp (i.e. 96.1% under scenario" 27% RES – high learning"). Summing up, effects are generally more pronounced in the case of low learning since then some wind or photovoltaic projects would not materialise whereas in the case of high learning other constraints may come into play that limit the overall diffusion of wind and PV.
- An even more pronounced impact on the optimal RES-E share is applicable for *electricity market design*, or, in other words, the capability of the system to provide flexibility to cope with high shares of variable renewables in electricity supply. Less or more flexibility of the power system and electricity market design in general, has technical and operational consequences and determines also the economic viability of RES-based electricity supply. As outlined in the methodology part of this report, specifically section 0, our modelling focusses on some core issues that impact RES-E integration, including grid development, electricity market design, and sector coupling / demand-side response. Under default optimal framework conditions / market design (i.e. scenario "27% RES (reference)) a high RES-E share (i.e. 49.7% by 2030, 95.1% by 2050) appears feasible from a technical perspective and at the same time this can be seen as economically viable. We contrast these findings with a scenario reflecting less optimal framework conditions – i.e. the so-called trend scenario (i.e. scenario "27% RES – trend market design") where for example a delayed grid development, no demand response and the implementation of capacity markets (leading to lower prices at the (energy-related) wholesale market) are postulated. It turns out that the optimal RES-E share is strongly affected: a decline of the RES-E share by 0.9 pp in 2030 (i.e. from 49.7% to 48.8%) and by 9.5% pp in 2050 (i.e. from 95.1% to 85.6%) is getting apparent. This underpins the often called need to adapt or redesign our market framework to foster renewable integration.
- Different *policy-related aspects* have been analysed within our modelling exam. For each topical subject under consideration one scenario has been defined to gain further insights on the resulting impacts as outlined below:
  - Within our analysis of how policy design may facilitate or hinder the uptake of decentral RES prosumers, we showcase the impact of whether or not a *prioritisation of decentral generation*, exemplified for the case decentral PV, will be given in future years post 2020. Under default conditions (i.e. reference scenario "27% RES") the assumption is taken that a prioritisation of decentral PV is maintained in future years, leading to a strong uptake of decentral PV in future years and, thus, affecting also total RES-E deployment. As discussed above, RES-E is expected to achieve a share of 49.7% in 2020, increasing to 95.1% by 2050. In contrast to above, in the absence of a special prioritisation of decentral

PV, meaning in practical terms that under scenario "27% RES – no prioritisation of decentral PV" we treat decentral PV systems (similar to other forms of central electricity supply) as a supply option to compete in the wholesale electricity market, decentral PV is lacking behind default trends. The optimal RES-E share by 2030 is consequently also affected, amounting to 49.2% which is 0.5 percentage points below the reference. Long-term (2050) impacts are even more pronounced: in 2050 the optimal RES-E share amounts to 90.6%, corresponding to a decline by 4.5 percentage points compared to reference.

- Pronounced impacts are also applicable for the scenario where *high carbon prices* (as a consequence of a major ETS reform) are prevailing (cf. scenario "27% RES – high carbon prices"). One scenario is consequently dedicated to assess how the (pending) reform of the EU's Emission Trading Scheme (ETS) may impact future RES developments and in particular the uptake of RES in the electricity sector (in competition to RES in other energy sectors). We assume here a strong uptake of carbon prices within the ETS in future years, building on outcomes of recent PRIMES modelling in this topical area. More precisely, we assume that carbon prices evolve as proclaimed by the PRIMES euco27 scenario, serving as a guiding scenario in line with energy and climate targets within the EC's 2016 winter package. In contrast, our default assumption used in modelling is that carbon prices increase moderately in the years up to 2050 (in accordance with the 2016 PRIMES reference scenario), cf. Figure 3. Results show that an increase in carbon prices leads to a faster uptake of renewables in the electricity sector. The scenario "27% RES – high carbon prices" shows a RES share of 51.3% by 2030, and a fully RES-based electricity supply by 2050.[6]
- *Strong 2030 targets for RES (and energy efficiency)*: Here, we analyse how the overall policy ambition for renewables (and for energy efficiency) determines the required uptake of RES in the electricity sector, exemplified by the assumed overall 2030 target set for RES within the EU. More precisely, we take the assumption that at EU level the 2030 RES target is set at 30% (instead of 27% as default).[7] This leads to an accelerated uptake of RES electricity, reaching a demand share of 54.6% (instead of 49.7% as default) by 2030. By 2050 there is however hardly any difference in RES-E deployment compared to the reference case. Reason is that the policy-driven demand for RES (in electricity and in other sectors) is no longer the determining factor for RES use under the scenario setting. In other words, renewables are expected to be cost-competitive by then and the "minimum RES-share" imposed in the modelling takes no effect at that point in time (independent if that is set at 27% or at 30%).

[6] A fully RES-based electricity supply, including a large set of variable RES generation, requires also a strong uptake of storage options and other flexibility solutions, so that they are available by that point in time.

[7] We are aware that this is still below the actually agreed one (i.e. 32% - as agreed in Council and Parliament during 2018) – but since it is here combined also with a lower energy efficiency target (i.e. 30% instead of 32.5%) this causes a comparatively similar level of overall RES ambition. Thus, in other words, the RES volumes required for meeting 30% RES in combination with a 30% energy efficiency target are comparatively similar than to strive for 32% RES combined with 32.5% energy efficiency. If accounted precisely, the required RES volumes by 2030 would be less than 3% smaller under the assessed combination (i.e. 30% RES, 30% EE) than under the politically agreed one (i.e. 32% RES, 32.5% EE).

The underlying technology mix

Complementary to the above, Figure 6 provides a technology breakdown of RES-E deployment at EU 28 level by 2030 (top) and by 2050 (bottom). Apart from the outlook toward 2030 and 2050 this figure also includes a comparison to the status quo (2015). Below we summarise key results:

- Apparently, onshore wind energy dominates the picture – both by 2030 and by 2050 the largest share of RES-based electricity generation will come from this particular technology, and also today (as of 2015) onshore wind plays a dominant role, achieving a slightly lower contribution as large-scale hydropower. Thus, electricity generation from onshore wind is expected grow from 258 TWh to a yearly generation potential of around 682 to 717 TWh by 2030. The trend continues towards 2050, reaching between 1,529 and 1,648 TWh by 2050.
- Large-scale hydropower (i.e. above 10 MW installed capacity) is the dominant RES source in the electricity sector by 2015. There is however only a limited potential available for further use. Normalised electricity generation from large hydro stands at 295 TWh today (2015). Scenarios indicate only a minor increase in generation to ca. 319 TWh by 2030 and to around 329 TWh by 2050. There is only a negligible variation across scenarios, indicating that the indicated increase in generation is economically viable. It also shows however that there is no additional potential available under the given economic and technical / environmental constraints.
- Offshore wind energy offers a promising potential. According to the scenarios assessed a strong increase is expected for offshore wind in the forthcoming decade – i.e. electricity generation will rise from 31 to at least 131 TWh by 2030. A strong increase is also presumed for the years post 2030. As a consequence, offshore wind is expected to reach between 798 and 884 TWh as annual generation potential by 2050.
- Apart from wind energy, photovoltaics is the other key technology in future years. Modelling indicates a significant increase in PV deployment, where electricity generation increases from 102.5 TWh in 2015 to 258 TWh under pessimistic circumstances (i.e. with no prioritisation of decentral generation) by 2030 whereas under default framework conditions a level of 294 TWh is achieved. Electricity generation from PV is expected in increase further until 2050, reaching between 487 and 795 TWh by then.
- Significant increases in deployment can be expected also for bioenergy under presumed "least cost" conditions. Electricity generation from bioenergy, comprising biogas, biowaste and solid biomass is expected to increase from ca. 171 TWh in 2015 to at least 235 TWh by 2030. That trend is prolonged in the years post 2030 and bioenergy will contribute to electricity generation with 500 to ca. 720 TWh by 2050 according to Green-X least-cost modelling.
- Other technologies like small-scale hydropower, geothermal electricity, tidal stream and wave power as well as CSP show only a minor contribution by 2030 and by 2050 under the underlying framework conditions where least-cost options are prioritised in modelling.

A comparison of the changes in deployment across scenarios shows that apart from specific non-prioritisation / discrimination – e.g. the scenario of "no prioritisation of decentral PV" where PV deployment is lowest among all assessed scenarios – in general terms the scenario of "27% RES – trend market design" leads to the lowest deployment of RES technologies in the electricity sector. In contrast to above, RES deployment generally peaks in the scenario "30% RES – strong EE" by 2030, and in the scenario of high carbon prices by 2050.

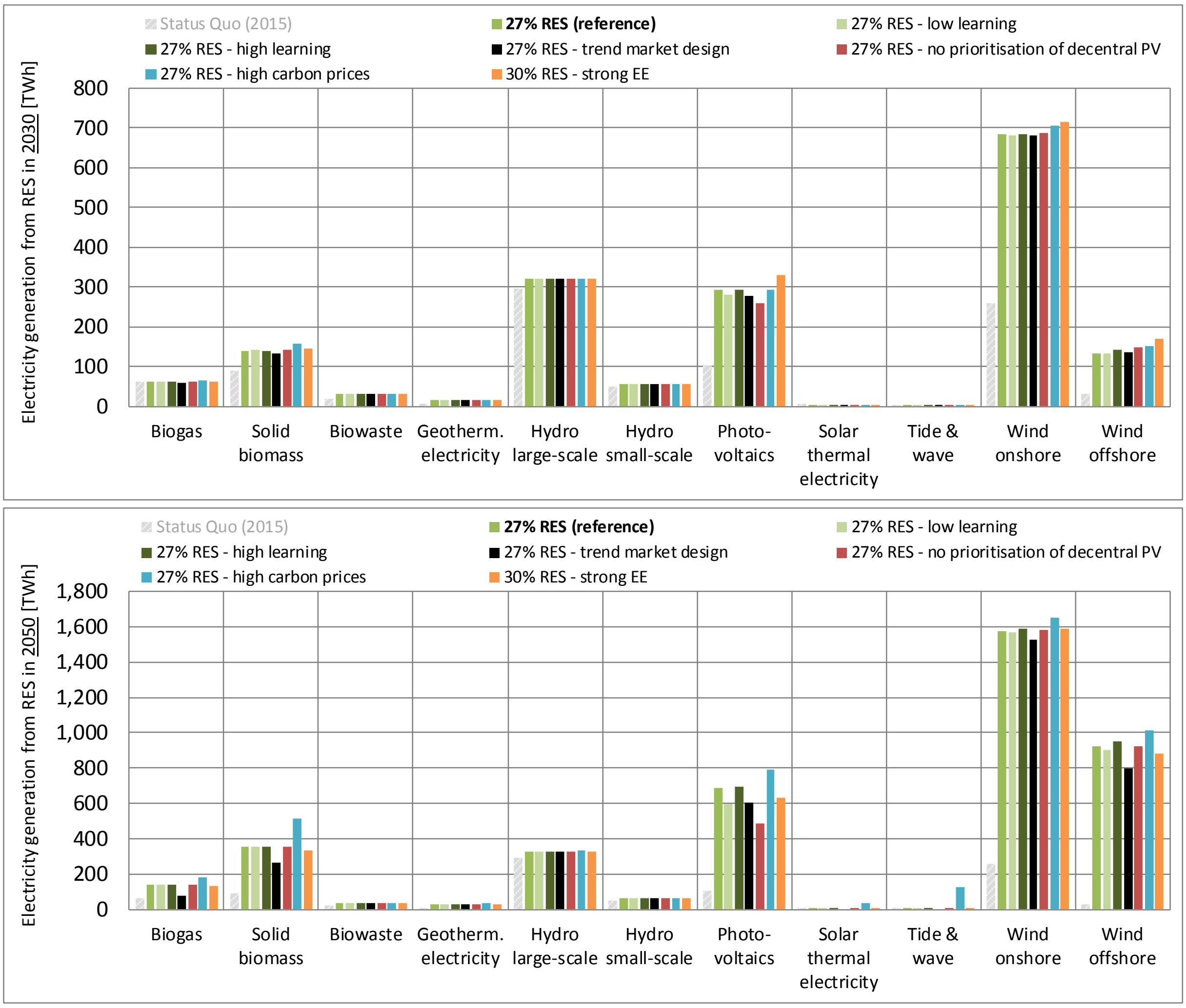

Figure 6. Technology-specific breakdown of RES-E generation by 2030 (top) and by 2050 (bottom) at EU 28 level for all assessed scenarios.

4 Synthesis and conclusions

This case study is dedicated to elaborate on *the diffusion of renewable electricity generation, aiming to gain insights on the suitable/optimal share renewables may take in Europe's future electricity supply.* Generally, renewable electricity generation (RES-E) is estimated to cover a high share of the future electricity demand in the EU. The possible diffusion of RES-E generation depends on the overall policy ambition in our combat against climate change, the relative costs of RES-E to its (low-carbon) alternatives, and the capability of the system to accommodate volatile generation. All these determinants are dynamic and therefore can change over time, and, most important, their impact on the optimal RES-E share has been analysed in the course of this case study. Below we report on some key findings.

Under assessed *default framework conditions* (i.e. 27% RES by 2030, optimal market design, etc.) a RES-E share of about 50% is reached in 2030.

Technological learning has an impact on these developments as observable from the related scenarios where either a 20% (compared to default) lower or a 20% higher learning rate is assumed for key technologies like wind energy and photovoltaics. As a consequence of the comparatively limited time span until 2030, only a small impact on the resulting 2030 RES-E share and on corresponding cost, analysed here through e.g. the resulting support expenditures, is applicable. The default RES-E share would for example decline by 0.5 percentage points by 2030 in the case of low learning, and the share increases by 0.2 pp in the case of high learning. By 2050 these effects are getting more pronounced: here low learning of wind and photovoltaics would cause a decline of the RES-E share by 2.8 pp.

An even more pronounced impact on the optimal RES-E share is applicable for *electricity market design*, or, in other words, the capability of the system to provide flexibility to cope with high shares of variable renewables in electricity supply. Less or more flexibility of the power system and electricity market design in general, has technical and operational consequences and determines also the economic viability of RES-based electricity supply. Our modelling focusses here on some core issues that impact RES-E integration, including grid development, electricity market design, and sector coupling / demand-side response. In a scenario reflecting less optimal framework conditions on these aspects it turns out that the optimal RES-E share is strongly affected: a decline of the RES-E share by 0.9 pp in 2030 and by 9.5 pp in 2050. This underpins the often called need to adapt or redesign our market framework to foster renewable integration.

Different *policy-related aspects* have been analysed within our modelling exam. For each topical subject under consideration one scenario has been defined to gain further insights on the resulting impacts as outlined below:

- Within our analysis of how policy design may facilitate or hinder the uptake of decentral RES prosumers, we showcase the impact of whether or not a *prioritisation of decentral generation*, exemplified for the case decentral PV, will be given in future years post 2020. Under default conditions (i.e. reference scenario "27% RES") the assumption is taken that a prioritisation of decentral PV is maintained in future years, leading to a strong uptake of decentral PV in future years and, thus, affecting also total RES-E deployment. In the absence of a special prioritisation of decentral PV, we treat decentral PV systems (similar to other forms of central electricity supply) as a supply option to compete in the wholesale electricity market. Consequently, decentral PV is then lacking behind default trends. The optimal RES-E share by 2030 is consequently also affected, declining e.g. by 0.5 percentage points below the reference by 2030, and by 4.5 pp by 2050.

- Pronounced impacts are also applicable for the scenario where *high carbon prices* (as a consequence of a major ETS reform) are prevailing. We assume here a strong uptake of carbon prices within the ETS in future years, building on outcomes of recent PRIMES modelling in this topical area. Results show that a stronger increase in carbon prices leads to a faster uptake of renewables in the electricity sector.
- *Strong 2030 targets for RES (and energy efficiency)*: Here, we analyse how the overall policy ambition for renewables (and for energy efficiency) determines the required uptake of RES in the electricity sector, exemplified by the assumed overall 2030 target set for RES within the EU. More precisely, we take the assumption that at EU level the 2030 RES target is set at 30% (instead of 27% as default).[8] This leads to an accelerated uptake of RES electricity, reaching a demand share of 54.6% (instead of 49.7% as default) by 2030. As recent modelling proves the optimal RES-electricity share would increase further to around 58%-60% if an overall RES share of 32% is aimed for by 2030.

[8] We are aware that this is still below the actually agreed one (i.e. 32% - as agreed in Council and Parliament during 2018) – but since it is here combined also with a lower energy efficiency target (i.e. 30% instead of 32.5%) this causes a comparatively similar level of overall RES ambition. Thus, in other words, the RES volumes required for meeting 30% RES in combination with a 30% energy efficiency target are comparatively similar than to strive for 32% RES combined with 32.5% energy efficiency. If accounted precisely, the required RES volumes by 2030 would be less than 3% smaller under the assessed combination (i.e. 30% RES, 30% EE) than under the politically agreed one (i.e. 32% RES, 32.5% EE).

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![SET-Nav Strategic Energy Roadmap]

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About the project

SET-Nav aims for supporting strategic decision making in Europe's energy sector, enhancing innovation towards a clean, secure and efficient energy system. Our research will enable the European Commission, national governments and regulators to facilitate the development of optimal technology portfolios by market actors. We will comprehensively address critical uncertainties facing technology developers and investors, and derive appropriate policy and market responses. Our findings will support the further development of the SET-Plan and its implementation by continuous stakeholder engagement.

These contributions of the SET-Nav project rest on three pillars: modelling, policy and pathway analysis, and dissemination. The call for proposals sets out a wide range of objectives and analytical challenges that can only be met by developing a broad and technically-advanced modelling portfolio. Advancing this portfolio is our first pillar. The EU's energy, innovation and climate challenges define the direction of a future EU energy system, but the specific technology pathways are policy sensitive and need careful comparative evaluation. This is our second pillar. Ensuring our research is policy-relevant while meeting the needs of diverse actors with their particular perspectives requires continuous engagement with stakeholder community. This is our third pillar.

Who we are?

The project is coordinated by Technische Universität Wien (TU Wien) and being implemented by a multinational consortium of European organisations, with partners from Austria, Germany, Norway, Greece, France, Switzerland, the United Kingdom, France, Hungary, Spain and Belgium.

The project partners come from both the research and the industrial sectors. They represent the wide range of expertise necessary for the implementation of the project: policy research, energy technology, systems modelling, and simulation.