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INNOPATHS

Innovation pathways, strategies and policies for the Low-Carbon Transition in Europe

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D3.6 Interactive Decarbonisation Simulator

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Version log

Version	Date	Released by	Nature of Change
1	25/09/2019	Panagiotis Fragkos (E3M)	First outline
2	01/11/2019	Panagiotis Fragkos (E3M)	Added content
3	20/11/2019	Panagiotis Fragkos (E3M)	Updated introduction and chapters
4	20/11/2019	Panagiotis Fragkos (E3M)	Added the section on ESDS tool functionalities
5	25/11/2019	Panagiotis Fragkos (E3M)	Final draft version sent for internal review
6	27/11/2019	Paul Drummond (UCL)	Review, comments
7	29/11/2019	Panagiotis Fragkos (E3M)	Finalisation and Submission of the draft version
8	15/03/2020	Panagiotis Fragkos (E3M)	Updated deliverable and include new sections
9	31/03/2020	Panagiotis Fragkos (E3M)	Finalisation and submission of the deliverable
10	08/05/2020	Panagiotis Fragkos (E3M)	Integrating responses to reviewer comments

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Definition and acronyms

Acronyms	Definitions
CES	Constant Elasticity of Substitution
ESDS	Energy System Decarbonisation Simulator
EC	European Commission
ETS	Emission Trading Schemes
EU	European Union
EV	Electric Vehicle
FIT	Feed-in tariffs
GDP	Gross Domestic Product
GHG	Greenhouse Gas
MS	Member States
NGO	Non-Governmental Organisation
T&D	Transmission and Distribution
TMT	Technology Matrix Tool
TRL	Technology Readiness Level

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1 Introduction

The INNOPATHS project uses a stakeholder engagement process to co-design and inform the development of sectorally- and technologically-detailed decarbonisation pathways by 2050 for the European Union and its Member States. To improve the accessibility of model results and facilitate and focus the stakeholder engagement process, E3Modelling developed the Energy System Decarbonisation Simulator (ESDS), which is an online tool that provides an intuitive insight into decarbonization strategies and low-carbon transformations in energy demand and supply for the EU-28 countries by 2050 and 2070. This deliverable describes in detail the ESDS online tool, which has been developed in the Task 3.2 of the INNOPATHS project and summarises some insights emerging from the application of the ESDS to explore low-carbon transition pathways for EU countries in the medium and longer term.

One of the objectives of INNOPATHS is to create new deep decarbonisation pathways with novel representation of policy and innovation process for low-carbon technology development for the EU. This effort also includes a systematic assessment of 'real-world' energy system challenges and opportunities. One of the outputs from this assessment in WP3 is the Energy System Decarbonisation Simulator (ESDS) online tool. The ESDS includes a comprehensive, fully interactive energy system model which is designed to be used by policy makers, industry representatives, researchers and the general public across Europe. It helps with designing decarbonisation strategies, assessing the impacts of specific energy and climate policy measures and investigating the synergies and trade-offs between emission reduction options in alternative low-carbon transitions, sectors and policy settings. The ESDS is designed to be an integrated, visual, interactive, transparent and online modelling tool to be used by policy makers, industrial stakeholders and civil society organisations/NGOs and general practitioners in energy across Europe and beyond. The tool provides relevant information on the projected energy system development under alternative policy scenarios and/or exogenous inputs (provided online by the user of ESDS). It integrates information from a variety of sources such as scientific literature and future-looking technology information and modelling scenarios.

E3-Modelling has been responsible for the design and development of the online modelling tool as well as the application programming interface, the visualisation and the final launch of the ESDS tool. PIK, UCL and Nice & Serious have provided comments throughout the design process. The prototype of the ESDS tool has been available in an early stage of the project in order to be used in the co-design process of WP3 (Deliverable D3.1). However, a full update of the tool with improved representation of energy technologies and climate policies, enhanced modelling and visualisation has been conducted in the last months. The current report describes the final version of the ESDS online tool (finalised in M40 of INNOPATHS[1]) that has been thoroughly tested during 2019 and 2020.

The report describes the functionalities and the key features of the Energy System Decarbonisation Simulator (D3.6) online tool that intends to be used by energy experts in order to gain insights on the impacts that different energy and climate policies have on the energy system. The tool as it stands at the date of delivery of deliverable D3.6 fully

[1] A four-month extension of the initial deadline was granted by the Project Officer without having any impact on other INNOPATHS tasks and deliverables.

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meets (and goes substantially beyond) the requirements set in the research plan of the INNOPATHS project.

The ESDS tool will help the understanding of the mechanics of decarbonisation and the implications of modifying key input assumptions (i.e. technology costs, socio-economic development, technology potential) and/or policy instruments (e.g. ETS pricing, efficiency standards, phase-out policies) for the EU Member-States. The ESDS online tool has the required functionalities to bridge the gap between rigorous science and applied decision-making, i.e. by ensuring easy interactions of the stakeholders with the tool and user-friendly visualisation of the ESDS results (including the calculation of policy relevant indicators and the comparison between two different scenarios). The ESDS online tool has incorporated customised functional features for all target audiences and sectors in its design and development. This is ensured via:

- Establishment of quality control processes both internally (by various leading experts of E3Modelling) and externally (by INNOPATHS partners)
- Extensive period of review and testing of the ESDS online tool both by E3Modelling and other consortium partners to ensure correct behaviour of the tool under very different assumptions and policy measures.
- Presentation of the logic, the features, functionalities and results of the online tool in various INNOPATHS meetings and workshops
- Organisation of a workshop with the EUCALC research project team in Athens in May 2019 to discuss the key elements differentiating the INNOPATHS ESDS tool from other online energy system calculators (like EUCALC).

The ESDS was designed to be an integrated, interactive and open online modelling tool to be used by policy makers, industry representatives, researchers and the general public across Europe. In the INNOPATHS proposal the tool was called "Interactive Decarbonisation Simulator" (IDS). However, after extensive internal and external discussions, we decided that Energy System Decarbonisation Simulator (ESDS) would more accurately describe the fact that the tool actually focuses on the decarbonization of the entire energy system of the EU and its Member States[2].

E3Modelling has finalised the work on the ESDS online tool by March 2020 (M40 of the project). This was followed by a period of review process – responding also to comments raised by INNOPATHS reviewers- to evaluate data, correct possible typos and align online instruction tutorials to make the web-based tool as user-friendly as possible.

The current version of the ESDS can be accessed at the following link https://innopaths-esds.eu/. Currently the ESDS is password protected. Credentials for user authentication are required and will be provided by E3Modelling on request. The tool is hosted at an in-house server of E3-Modelling facilitating the constant update of the tool in order to increase its scope and maximise its relevance and usefulness. Having direct control over the tool will also facilitate E3Modelling's efforts raising funds to keep the ESDS tool up to date and to expand its functionalities. The ESDS tool will show direct links to the INNOPATHS project official website. A system of open access for users through a username and password linked to an email address is provided, in order to facilitate user

[2] The content and process used in this task has not changed. We have only modified the name to better reflect the added value of the tool.

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interactions and enable the ESDS online users developing, visualising and comparing their own scenarios.

The full ESDS online tool (input data, assumptions, and documentation) is made publicly available (anyone will be able to access its content) as the final tool and its functionalities are updated and the review process is finalised. An institutional email address (esds@e3modelling.com) is created to receive questions about the tool as well as to facilitate the direct contact between users and administrators of the ESDS. This process allows us to track and monitor the use of the ESDS tool and the development of scenarios by various online users.

2 Objectives and innovation of the ESDS tool

The objective of the Energy System Decarbonisation Simulator (ESDS) online tool is to provide useful and reliable information on low-carbon transition pathways to policy makers, industry representatives, researchers and the general public across Europe and beyond. In this way, it aims to facilitate the understanding of challenges and opportunities related to the EU's low-carbon transition and explore the synergies and trade-offs between technological options and mitigation strategies in different low-carbon transition policy contexts.

This tool has the goal of giving policy makers, the general public and industry associates a more intuitive understanding of different decarbonisation strategies, and the impacts of different choices, policy measures and targets in the various sectors and EU Member States. The online ESDS tool is interactive; tool users can modify key input assumptions (i.e. costs for the PV technology or the evolution of electricity demand in a country) and/or policy instruments (i.e. ETS pricing, efficiency standards, RES Feed-In-Tariffs, coal or nuclear phase out etc.) and the ESDS will project the effects of these changes on the energy system, fuel mix, deployment of low-carbon technologies, CO_2 energy-related emissions, investment requirements and energy costs and prices. The tool invites the web users to interact with it; by designing different decarbonisation scenarios/strategies, the user can quickly get a robust understanding of which policy measures have large effect and which don't and where potential bottlenecks might lie (i.e. in hard-to-abate sectors). In order to achieve a balance between segmentation, interactiveness and low running times, the ESDS results are slightly more aggregated relative to the very detailed energy-economy model scenarios developed in INNOPATHS (i.e. with the large-scale PRIMES energy system model), but full internal consistency between input and output of the ESDS scenarios is ensured at all times.

The ESDS online tool essentially takes up the idea of previous tools, such as the DECC 2050 Energy Calculator (see: http://2050-calculator-tool.decc.gov.uk/#/home). However, the ESDS goes an important step further and moves beyond simplistic calculators, as the underlying methodology is significantly improved; the backend model is a simulator of the entire energy system and includes innovative, intelligence features which are not part of current calculators (i.e. causality, system dynamics, explicit representation of policies, interactions of energy demand and supply, market-driven prices etc.). The parameters and elasticities used in the ESDS underlying model can be calibrated to the results of state-of-the-art complex energy-economy models, mainly PRIMES projections for each EU Member-State (for instance in the "Baseline" scenario simulation). The user of the ESDS online tool is able to change the values of all input assumptions (i.e. technology costs, behavioural parameters, exogenous investment in plants, socio-economic assumptions)

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and the values of policy variables, such as ETS carbon prices, renewable support schemes, Feed-In-Tariffs, efficiency standards, potential limits and/or potentials for specific fuels and technologies, and their improvement and market deployment. The ESDS calculates the resulting energy system developments, energy mix by sector, technology deployment, CO_2 emission reduction and energy system costs, split into investment costs, energy purchase costs, operation and maintenance costs as well as electricity prices (by type of consumer). The model runs in the background and the results are visualised through the online interface of ESDS, including appropriate tables, figures and charts including the possibility to compare two contrasting scenarios. The sections below provide a detailed overview of the methodology and functionalities of ESDS.

To summarise, the key objectives of the online ESDS tool are:

- Improve the transparency of long-term energy system modelling, underlying data and input assumptions, thus responding to recent criticisms by researchers.
- Facilitate Learning processes for various practitioners in the energy field (including policy makers, industrial representatives, NGOs, researchers). In the future, the online tool can be used to facilitate capacity building and educational activities in various countries, with the parallel development of educational material appropriate for higher education.
- Provide coherent insights to tool users and stakeholders about:
    - Possibilities and potentials of decarbonisation by sector in each EU country, exploring the complex interlinkages between demand and supply sectors
    - Policy instruments and their impacts on projected fuel mix, energy system development, CO_2 emissions, investment and energy system costs
    - Sectoral allocation of emission mitigation effort and deployment of clean energy technologies by sector
    - Synergies and trade-offs between alternative emission reduction options in the low-carbon transition context
    - Constraints and bottlenecks of low-carbon transition, i.e. hard to abate emissions in specific sectors
- Ensure User-friendliness and easy interactions with the user & Open-access to both input data and modelling output through appropriate visualisation
- Integrate high granularity in terms of technologies, sectors and countries to provide consistent assessment of decarbonisation strategies and low-carbon transition pathways (relative to other online “calculator” tools)
- The tool is not intended to substitute fully-fledged energy-economy models, but to provide robust and useful insights through easy, online interactions with the users and without the need to understand complex modelling methodologies and data handling and processing.

After extensive discussions within the consortium, it is clarified that there is no fundamental over-lapping of the INNOPATHS ESDS online tool with other similar tools

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(i.e. the DECC 2050 Energy Calculator[3] or the European Calculator[4], developed in the H2020 research project EUCALC). The ESDS will service a uniquely useful purpose among similar online tools that have been developed to date, as ESDS:

- Introduces innovative features in the underlying modelling methodology (i.e. elasticities, market-driven price formation, causality, dynamics, interactions across sectors, representation of energy and climate policy measures).
- Uses the most up-to-date data for the underlying energy system modelling including recent data on energy technologies for all sectors
- Enables the users to design their own pathways, assess alternative policy instruments and explore synergies and trade-offs as well as the complexities, challenges, impacts and opportunities of low-carbon transition for EU countries
- Improves user-friendliness, visualisation and web presentation of previous similar online tools

In May 17 2019, a technical workshop was held together with the EUCALC H2020 project to ensure there is no fundamental over-lapping of the two online tools and discuss the uniqueness of the ESDS online tool, as suggested by the mid-term INNOPATHS review. The workshop was well-attended by more than 20 practitioners in the energy field (EUCALC and INNOPATHS partners). The extensive discussions served to clarify the unique purpose of the ESDS online tool and the aspects that need to be improved in order to ensure maximum legitimacy and usability of the tool. Based on the outcomes of the workshop and the comments received from the INNOPATHS mid-term review, the prototype of the ESDS online tool (D3.1, submitted in M9 of the project) has been fully re-designed and significantly expanded and improved by introducing innovative intelligence features in the underlying modelling methodology (i.e. elasticities, price formation, causality, dynamics, representation of energy and climate policies, interactions across sectors). The simple energy system accounting framework (that is included in ESDS prototype in D3.1) has been significantly enhanced by incorporating intelligence features moving towards rigorous energy system modelling based on PRIMES model (i.e. causality, dynamics, capital stock and vintages, interactions among energy demand and supply sectors, energy price formation mechanisms). In addition, ESDS integrates a wide spectrum of recent data, both on energy balances and fuel mix of the EU-28 countries (from the EUROSTAT and IEA databases) as well as on the future development of technical and economic characteristics of energy, electricity and transport technologies.

The key techno-economic assumptions included in PRIMES (that directly fed into the ESDS tool) underwent a rigorous and extensive consultation with industrial stakeholders in mid-2018. This is particularly important for the "new" energy-related technologies and disruptive mitigation options which currently have limited application in the energy system and are at low TRL levels- which implies high uncertainty on their future costs and performance. In order to obtain as much as possible consistent, realistic and accepted estimates of the (present and future) techno-economic features of both "conventional"

[3] http://2050-calculator-tool.decc.gov.uk/#/home
[4] http://www.european-calculator.eu/

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and "disruptive" energy technologies, we performed a comprehensive literature-based research, the results of which then underwent an extensive consultation with a large number of stakeholders from Europe (i.e. policy makers, industrial representatives, energy practitioners) on the costs and performance of energy-related technologies[5]. This was performed as part of the EU-funded ASSET project[6] and the technological pathways for all energy technologies are incorporated in the ESDS online tool developed in INNOPATHS context. The stakeholder consultation included experts for conventional and new technologies (hydrogen, CCUS[7] and bio-methane experts, etc.) as well as representatives of industrial associations. Details on the updated techno-economic dataset used in ESDS are provided in Section 4 below.

The improved ESDS tool is of high quality and provides an improved understanding of the challenges, impacts, complexities and opportunities of low-carbon transition for EU countries compared to similar online tools ("energy calculators"); the latter are simplistic energy accounting frameworks where the user defines everything exogenously (fuel mix shares, energy efficiency achievement ratios) usually for a single year. Most existing energy calculators do not provide the possibility to analyse the impacts of specific policy measures (i.e. the EU ETS or efficiency standards) and thus they cannot be used to explore policy-relevant questions in the EU context. These accounting tools lack drivers and causality for the assumed energy developments and target achievements regarding RES, efficiency and emission reduction; they also lack dynamics (i.e. changes in capital stocks) and any interaction between supply and demand for the formation of energy prices. In addition, current online energy calculators provide no evidence regarding how much to change every indicator (i.e. energy mix or efficiency ratio) or whether it is possible in reality, which policy measures would drive such a change and what will be the associated impacts. Therefore, non-expert users may be misled to incorrect insights and conclusions as they can easily change exogenously all indicators. This is exactly the main gap that we fill with the improved Energy System Decarbonisation Simulator online tool, which includes the causality and structural features of an analytical large-scale energy system model in a compact size through (appropriately estimated) elasticities; the latter represent the more complex relationships of the PRIMES energy system model. In addition, the tool represents energy and climate policy instruments, incorporates drivers of change (economic, technical and behavioural), causality, modularity and market-driven energy prices, as well as dynamics for capital stock, technology vintages and system inertia. The detailed mathematical modelling and data collection and consolidation has been finalised (described in detail in Section 3). Using the ESDS tool, the user is able to understand the internal mechanisms, the challenges, opportunities and potentials as well as the impacts of specific low-carbon transition pathways and energy and climate policies. The price to pay for the sophistication is that the user will have to tolerate slower computer running times relative to other energy calculators (i.e. about 3-4 minutes in the worst-case scenario); but the user can visualise, compare and download the full results of the

[5] The report of the stakeholder consultation and the assumptions are available here: https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

[6] https://asset-ec.eu/

[7] Carbon Capture Utilisation and Storage

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scenarios he/she developed and get a robust understanding of the impacts of low-emission policies and strategies.

Until now, due to time constraints and as the final tool includes significant improvements relative to the INNOPATHS Description of work (i.e. more granular modelling, causality, policy representation, extension to 2070[8]), stakeholders have had limited involvement in the development of the ESDS tool, except for the extensive stakeholder participation in technology cost evaluations, also used in the Technology Matrix Tool (TMT). In addition, during the last months, experts of E3Modelling, INNOPATHS partners and reviewers tested the behaviour of the ESDS tool under varying assumptions and policy measures. This aspect has been improved in the final year of the project, as the ESDS tool is open to testing, commenting and review by INNOPATHS partners, the European Commission, relevant stakeholders and the wider scientific community. In particular, the ESDS tool is publicly presented in the INNOPATHS high-level final conference to a wide range of stakeholders, including policy makers, industry representatives, researchers, civil society organisations and general practitioners in energy across Europe and beyond. In addition, we plan to submit for a demonstration session for COP26 in 2021, while the ESDS tool was also presented in the series of national events organised by INNOPATHS (at least in Greece), where project results were presented during 2020 and 2021 to local energy stakeholders and policy makers and to a wide audience.

The ESDS tool is based on PRIMES data and projected low-carbon transition pathways, as a coverage of all EU-28 countries is required up to 2050 and 2070. PRIMES is a well-established energy system model that has been extensively peer-reviewed, has a very high sectoral, technology and policy granularity, runs individually for all 28 EU Member States and has been extensively used by the European Commission (EC) for energy and climate policy impact assessment (i.e. for the Energy Roadmap 2050[9], the quantitative assessment of the 2030 Energy and climate policy framework, and the recent "Clean Planet for All" long-term strategy[10]). The Reference scenario included in the ESDS tool is based on the Baseline scenario developed with PRIMES in the Impact Assessment of the "Clean Planet for All" long-term strategy.

Overall, the desired usability and applicability of the ESDS online tool to a wide range of potential users is ensured by investing considerable effort to develop a state-of-the-art online tool of very high quality, including robust and rigorous energy modelling, up-to-date data, realistic projections and policy measures and improved visualisation and user interactions. The high quality of the ESDS tool together with the easiness to update (periodically) and its distinguishing features compared to similar online "energy calculators" will ensure its use by a wide range of relevant stakeholders and energy practitioners and its durability beyond the duration of INNOPATHS.

[8] The extension of the ESDS tool to 2070 was considered necessary, due to the shift of the EU energy and climate policy towards the goal of "climate neutrality" by mid-century as demonstrated in the recent "Clean Planet for all" long-term strategy (November, 2018) that included detailed energy system modelling until 2070 for the first time.

[9] https://ec.europa.eu/energy/sites/ener/files/documents/roadmap2050_ia_20120430_en_0.pdf

[10] https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

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3 Overview and Main Features of ESDS tool

3.1 Main Features of the ESDS tool

The basic idea of the ESDS is to build an online tool and platform where stakeholders, policy makers and other users can explore the impacts of energy and climate policies on energy system development, CO_2 emissions and energy costs in EU countries and develop a full quantitative understanding of the key decarbonisation challenges and opportunities for specific sectors and EU countries. In addition, the users can create online full-scale scenarios by modifying exogenous assumptions and/or policy measures, running the ESDS modelling tool and exploring the scenario results with appropriate visualisation tools (including comparison of ESDS results for two contrasting scenarios). In this sense, the tool allows for online, web-based and quick interactions with the users and can thus facilitate an improved understanding of the complexities, potentials, challenges and opportunities of energy system transition and can be used for capacity building activities, especially in higher education.

The development guidelines for designing the ESDS online tool adhere to the following principles:

- It is structured to present multiple dimensions in a clear and concise way: model inputs vs outputs, different scenarios (developed by the web user), spatial, sectoral and temporal dimensions of parameters and variables (including the possibility of different aggregation levels).
- It is flexible, so as to fully adapt to the user needs.
- It is user friendly with appropriate visualisation tools and other functionalities (including the possibility to compare results and inputs of two alternative scenarios) and facilitates and supports web-based user interactions so as to achieve the desired dissemination and maximum usability by the wider community and relevant stakeholders.
- It uses reliable and rigorous modelling and up-to-date data related to the energy system and energy, electricity and transport technologies. To this end, the underlying database of the ESDS is largely based on the consolidated PRIMES dataset that underwent evaluation by various industrial stakeholders and policy makers in 2018, while the comprehensive and reliable modelling in fully ensured (details are included in next sections).
- It ensures quick interactions (quick running times) with the web user. Despite the sophisticated, fully-fledged energy system modelling for all EU-28 countries, every attempt was made to reduce the running time to below 3-4 minutes.
- It is policy relevant as it explicitly represents a wide spectrum of energy and climate policies in order to ensure increased usability by policy makers and other stakeholders (i.e. quantification of policy-relevant indicators, ability to assess the impacts of specific energy and climate policy measures).
- It is tailored to meet the needs of specific target audiences. This is accomplished through the provision of two distinct modes of using the online tool, i.e. the Full-

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scale run (where the user can change more than 200 input assumptions by country) and a Quick scenario mode where non-expert users can modify only a sub-set of input assumptions.

The user is given complete control over which scenario to design, for which country, which parameter to change (either as an exogenous assumption or as a policy variable), which running mode to choose (full-scale or quick run mode), which input or output variables to visualise and which spatial, technology, sectoral, or temporal aggregation to choose. Given such a high degree of freedom, the level of complexity of the user-generated information is prone to increase exponentially with the input parameters. To tackle this issue, considerable discussion among the project team in E3Modelling was conducted in order to decide the most efficient approach for handling this level of data complexity without limiting the user choice while alternative visualisation formats (i.e. different chart formats) play a crucial role. Displaying the results through a variety of chart types with enhanced visualisation techniques, allowing for appropriate filtering of variables, comparing the results of different scenarios, representing scenario results in different graphs, multiple chart generation (especially to compare the results of two alternative scenarios) etc. are examples of features included in the ESDS tool enabling to display the underlying model-based data and output as clearly as possible. Additional details about the features included in the ESDS tool can be found in the sections below.

Some of the key features of the ESDS tool can be summarised as:

- Ensures full economic reasoning and causality between economic, technological, behavioural and policy drivers with projected developments for energy supply by sector, fuel mix, investment in energy technologies, interactions between demand and supply and market-driven pricing of energy products
- Represents a wide spectrum of energy and climate policy measures influencing the future development of the EU energy system (i.e. ETS pricing, coal phase-out, RES support schemes)
- Quantifies the impacts of specific policy measures on the energy mix, technology costs and deployment, CO_2 emissions, power generation mix, investment requirements and energy costs and prices
- Mimics results for low-carbon transition pathways produced by PRIMES, despite that ESDS does not include all PRIMES mechanisms, details and granularity. This is achieved through appropriately estimated elasticities for each EU country.
- The user can build whatever scenario he/she wants by modifying (one or more) exogenous assumptions and the intensity of policy measures
- The ESDS online tool has a large disaggregation in terms of countries (all EU-28 Member States are represented separately), energy sectors, technologies (more than 60 energy-related technologies are represented) and policy measures

The ESDS includes full accounting of technology vintages and thus allows for improved representation of low-carbon transition dynamics and energy system inertia. The behaviour of various energy system agents, i.e. consumers, energy utilities, technology

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providers, is based on economic optimisation by sector (i.e. minimisation of energy costs or maximisation of profits for firms). The ESDS incorporates the concept of representative agent by sector and sub-sector, with modelling of consumer heterogeneity based on subjective discount rates differentiated by type of consumer and perceived costs (representing barriers faced by consumers)[11]. In this way, the ESDS tool can explore the impacts of policies alleviating market and non-market barriers towards energy efficiency and low-carbon transition as well as sector-specific policy measures targeting sectoral transformation, i.e. energy savings in buildings through retrofits, uptake of heat pumps and electric cars, thermal insulation etc.

One of the distinctive features of ESDS relative to other online "energy calculator" tools is the combination of behavioural modelling (following a micro-economic foundation) with engineering aspects, covering all energy sectors and markets. The model has a detailed representation of energy and climate policy instruments, including:

- EU ETS carbon pricing
- Energy pricing, taxes and subsidies for all energy products
- Energy efficiency and CO_2 standards by sector (buildings, industry, transport)
- Targets for CO_2 emissions, RES uptake and energy efficiency improvements
- RES promoting policies, including Feed in Tariffs
- "Virtual" promoters/subsidies to promote specific decarbonisation options (i.e. renewables, CCS technologies, green hydrogen)
- Phase-out policies, i.e. for coal or nuclear power plants
- Innovation policies (leading to cost reductions for low-carbon technologies)
- Mandates and regulations specified by sector and Member State

The tool can handle multiple policy objectives, such as CO_2 emissions reductions, energy efficiency, renewable energy targets and provides pan-European simulation of energy and electricity markets. The ESDS model is based on market equilibrium for all sectors with explicit pricing of energy products. It simulates detailed interactions between energy demand and supply through market-derived prices by type of consumer (i.e. electricity prices applied to industries or households).

The ESDS tool offers the possibility of handling market distortions, barriers to rational decisions, consumer behavior and market coordination issues and it has full accounting of costs (CAPEX and OPEX) and investment on technologies and infrastructure needs. The model covers the horizon up to 2070 in 5-year interval periods and includes all EU-28 Member States individually. ESDS is designed to analyse the complex interactions within the energy system in a multiple market framework. Decisions of energy agents are formulated based on micro-economic foundation (utility maximization, maximisation of costs and market equilibrium) embedding engineering and technical constraints (i.e. load duration curves, power plant constraints, flexibility and balancing requirements) and explicit representation of technologies and vintages. Thus, the ESDS online tool is well

[11] For additional clarifications of these issues, please see https://e3modelling.com/modelling-tools/primes/

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placed to simulate medium and long-term transformations of the energy system (rather than short term) and includes a detailed assessment of resource potential by type and technology learning. To simulate long-term structural transitions, the model is fully equipped with a set of innovative clean energy options, including hydrogen and clean synthetic hydrocarbons (e-gas and e-liquid fuels), electricity storage, Negative Emission Technologies (i.e. Biomass with CCS), Carbon Capture, Use and Storage (CCUS), and deep electrification of energy uses in transport, buildings and industrial sectors.

The basic structure of the ESDS modelling tool can be found below:

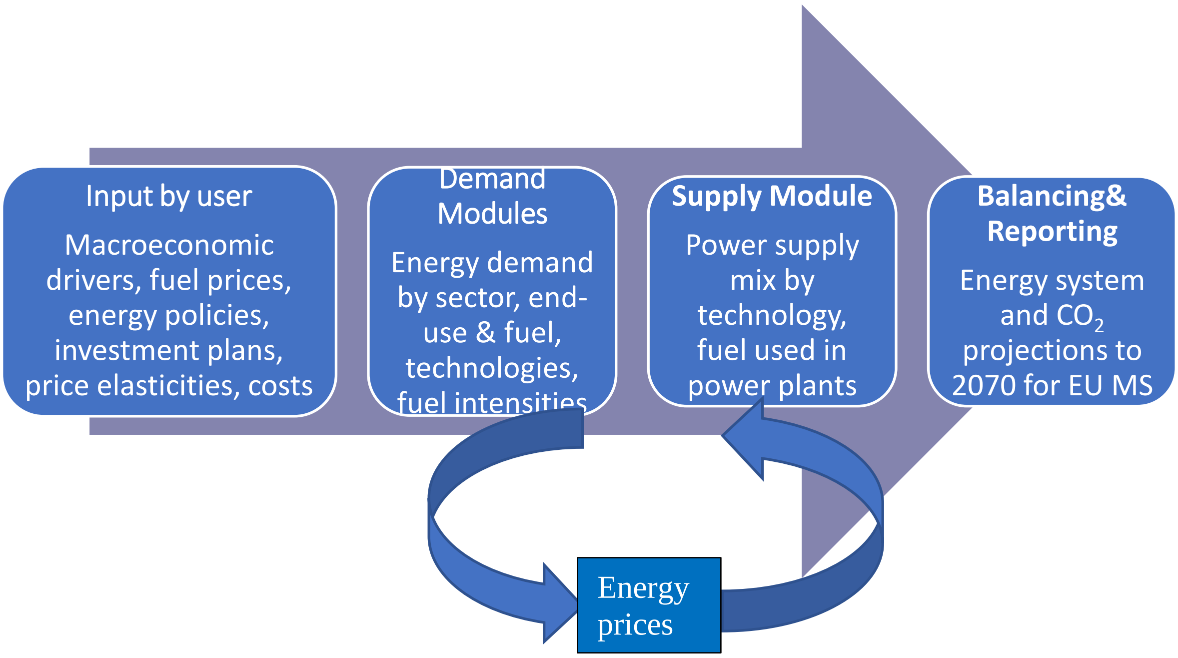

Figure 1: Basic structure of the ESDS modelling tool

3.2 Modelling Methodology and Structure

The ESDS includes the causality and structural features of a fully-fledged energy system model (PRIMES) in a miniature size through appropriately estimated elasticities to represent the more complex relationships of PRIMES energy system model. The tool incorporates causality and represents policy instruments, drivers of changes, modularity and market-driven prices, as well as dynamics for technology and capital stock. The ESDS tool covers all EU-28 countries (i.e. the current 27 EU Member States plus the UK) separately and has a high sectoral, country, policy and technology disaggregation. The underlying model is a linear programming model running in Python and fed by data in CSV format or any other Excel-compatible format. The model runs for all EU-28 countries separately and provides results for the period 2020 to 2070 with five-year time step. All the data, input and output are stored and the user can online visualise, compare and download the scenario projections and data (simulated with the ESDS). In this way, the web user would understand the internal mechanisms, the complexities, difficulties and possibilities, as well as the impacts of different low-emission transition pathways and energy and climate policies. ESDS includes dynamics (technology vintages, capital stock changes), drivers and causality of the assumed achievements regarding RES deployment, fuel mix and reduction of CO_2 emissions. The ESDS online tool includes a fully-fledged

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energy system model that provides projections for energy system development for the EU countries. The key features of the modelling tool are:

- It is comprehensive, as it includes high sectoral, technology, country and policy granularity and representation
- It has short running time (i.e. up to 3-4 minutes) which is key for online tools to increase its wide usability by relevant stakeholders and policy makers
- It is comprehensible by the users as it is accompanied by an online tutorial
- It is customisable, as it has two operation modes to meet specific needs of expert and non-expert users
- It allows for online interactions with the users with improved visualisation functionalities allowing also for comparison between scenarios

The modelling part of the ESDS tool is comprised of two main components that interact to form a market equilibrium through endogenously-derived energy prices:

1) Energy demand modules, which cover all energy end-use sectors (households, services, industries, transport by mode) in sufficiently high detail.
2) Energy supply modules, that include a fully-fledged power supply model (power plants and electricity transmission) as well as other energy supply activities (refineries, industrial boilers, district heating). The energy supply modules are developed on the basis of cost minimisation to meet the demand for electricity and other energy carriers as derived from energy demand modules.

Therefore, the ESDS can simulate the potential synergies and trade-offs between different mitigation options to meet a given CO_2 emission reduction target. In the ESDS model, each sector minimises its total costs (including CAPEX, OPEX, fuel and CO_2 emission costs) subject to a spectrum of constraints, including: useful energy demand in each sector, dynamics of technology and equipment vintages, potentials and constraints of specific fuels and technologies, substitution possibilities between technology options, power-system constraints (reserve margin, ancillary services, ramping), energy and climate policies and targets. The pricing module determines the prices for energy carriers (electricity, steam, hydrogen) by sector and type of consumer; these prices are fed back into the energy demand modules. The demand-supply interactions ensure that market equilibrium is reached with market-driven energy prices. The ESDS projects energy consumption by sector and by fuel, power generation mix, technology deployment, energy-related investment and energy system costs into the future based on a series of input assumptions and policy targets and measures, which are determined by the tool user. The ESDS solves as linear programming, as the NLP[12] functions currently used in energy models (i.e. Logit, CES[13] or Weibull) are linearized (see section 3.3) ensuring faster run of the model and no numerical problems during the solving phase of the relevant optimization problems.

Consumer choices involve trade-offs between upfront investment costs and operating costs. For these capital decisions, the ESDS model uses the weighted average cost of capital (WACC) and subjective discount rates (differentiated by type of agent) to

[12] Non-Linear Programming

[13] Constant Elasticity of Substitution

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annualise the upfront costs and compare them with annual operating and maintenance costs. The aim is to mimic decisions by individuals as realistically as possible, through the use of subjective discount rates and risk premium factors, which reflect opportunity costs of drawing funds by the private sector or individual consumers, uncertainty, lack of information and limited access to capital markets. For this reason, the ESDS includes the possibility that the online user changes the individual discount rates[14] due to policy implementation, mirroring how certain policy instruments may reduce uncertainties or decrease financing costs to facilitate economic decisions for investing in technologies with high upfront costs. The various consumer types also see other, non-engineering costs ("perceived costs") that represent technical uncertainty, risk of high costs of maintenance in case of not-yet mature technologies (i.e. Carbon Capture and Storage or hydrogen), easiness of technology application or compliance with regulations, etc. These perceived costs are assumed to decline over time as new technologies become commercially mature. The decisions of agents also depend on energy and climate policy measures (that are defined by the user of the ESDS), such as: energy taxes and subsidies, promotion of new technologies (reducing perceived costs or increasing support for specific mitigation options), and renewable energy or energy efficiency standards, policies that ease financing for low-emission technologies, etc.

3.3 Energy demand modules

The ESDS demand modules project final energy that needs to be consumed by industrial, residential, services, agriculture, and transport sectors to satisfy the useful energy services in each sector. The sectoral developments are based on macro-economic projections (through appropriate elasticities) inserted by the user and are expressed as: activity in ktn of product and gross value added (industry), activity by transport mode in passenger-km and tonne-km (transport), activity in useful energy services (buildings). The formulation by sector embeds engineering details, technical restrictions, economic considerations, and consumer behaviour in the optimisation problem. Demand for energy commodities is a means for obtaining useful services (i.e. thermal comfort, mobility, metal production, lightning), driven by economic activity, energy prices and living conditions. Energy demand evolution by sector depends also on the behaviour of firms and/or individual consumers and by the investment decisions and technology choices at the consumer level.

For each energy demand sector, a representative decision-making agent operates, who optimizes an economic objective function, i.e. utility maximisation (for households and private transport), cost minimisation for industrial, tertiary and freight transport sectors. The decision on fuel, equipment and technology mix follows a nested budget allocation problem, where useful energy demand is determined first at the sectoral level (i.e. services from energy such as temperature in a house, lighting, industrial production, mobility etc.). Useful energy demand projections are based on the evolution of sectoral activity, energy price developments and the (user-defined) elasticities. The projections also consider saturation dynamics that depend on the income of households. Useful energy demand is then decomposed into specific processes and uses (e.g. space heating, water heating, industrial processes etc.) following a tree structure and distinguishing sub-sectors to get a more accurate representation of the stylised agent. For the buildings sectors, the ESDS

[14] As discount rates can be criticized as unethical for future generations, the ESDS allows the tool users to modify the values for discount rates (and even choose zero discount rates).

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modelling tool distinguishes: Space heating, cooling, water heating, cooking and electric Appliances (refrigeration, lighting, dish washers, dryers, and other types of appliances). For the transport sector, the ESDS distinguishes between passenger and freight transport modes and covers: Private cars, public road transport, rail transport, freight road transport, aviation, and navigation. The section 4 and the annex of the deliverable include details on the country, sectoral and technology representation of the backend ESDS model.

The notion of the "representative" consumer is commonly used in energy system models and is well known and widely accepted in economic modelling. In the backend ESDS model, the detailed decomposition by sector, sub-sector and energy use, aims at defining decision cases in which the discrepancy of decision conditions becomes smaller, but this decomposition is limited by available statistics. Therefore, even within each sector the optimality of decisions related to technologies or fuels may vary across the individual decision-makers operating in that sector. This of course is due to the varying conditions of energy use for each individual case.

To represent the fact that a number of decision makers with varying conditions operate in a sector, the backend ESDS model introduces a way of aggregating individual decisions to derive the overall "average" choice of the representative consumer by sub-sector. This way, even unlikely choices of seemingly higher costs will have a small share, due to specific conditions faced by some consumers. In the backend model, this is formulated with the introduction of diversity in the function that aggregates the consumer choices. While the individual consumers do make discrete choices, the representative consumer is more likely to choose a mix from technologies and fuels. This formulation combined with the high granularity in terms of sectors, sub-sectors, energy uses, modes and technologies incorporated in the backend model implies that ESDS can capture different stakeholder interests and different consumer choices with high realism.

Demand is modelled in terms of useful energy services, and in terms of final energy commodities, ensuring energy balance between useful and final energy. Useful energy requirements at the level of uses and processes are linked to the consumption of final energy products. The representative agent in each sub-sector makes choices among fuels/ energy carriers, technologies and energy savings in order to minimize the total costs for meeting the useful energy requirements. The formulation includes the possibility of choice between purchasing ready-to-use fuels or energy carriers (i.e. electricity) and self-producing energy where this is possible.

Energy savings possibilities are represented in each demand sector and sub-sector and follow engineering-economic representations, including the possibility of shifting towards more efficient technologies, equipment, vehicles and appliances. Substitutions are possible between processes, energy uses, energy forms, technologies and energy savings. The adoption of technologies depends on their relative costs, but also on policy measures (specified by the ESDS online user) like efficiency standards, energy taxes, carbon prices and phase-out policies and is dynamic keeping track of technology vintages and stock-flow investment in each sector (transport, buildings, industries) and sub-sector.

The ESDS represents different technology types in the buildings sector (that can operate using various fuels and energy carriers), including: boilers, heaters, heat-pumps, stoves, micro-CHP, distributed heat, chillers, cookers etc. The ESDS modelling tool represents

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possible fuel, technology and equipment substitutions and energy efficiency at various levels in the residential and tertiary sectors as well as renovation strategies for buildings (i.e. thermal insulation, deep building retrofits). The tool puts high focus on the renovation strategies in the buildings sector (residential and services), as the rate and deepness of renovation are crucial drivers towards energy efficiency improvements in EU countries. The modelling tool includes alternative renovation strategies, ranging from “light” to “deep” renovation strategies, which are all linked to specific investment costs and specific energy savings. The demand modules of ESDS account for technological progress, as each activity/energy use can be carried out by different technology and equipment type characterised by different investment costs sand energy intensities. Technology types in each sector have been classified as ordinary, improved, advanced and future according to their investment costs and energy efficiency ratios. The choice of the equipment and technology mix is influenced by their costs, efficiencies, policy measures and parameters representing perceived and hidden costs, as well as learning by doing factors. These parameters change over time, may vary by scenario and are defined by the ESDS user.

In reality, individual consumers make discrete choices regarding, for example, building renovation, the heating technology or the purchase of a car. The ESDS tool (and other energy system models) cannot capture the idiosyncratic behaviours of individuals, as data are not available for individual consumers; thus, the “representative decision-maker” hypothesis persists. To capture idiosyncrasies and heterogeneous features of individual consumers within each class of representative decision-makers in the building and transport sectors, we assume that multiple choices co-exist with frequencies that follow a given distribution, such as Weibull or Logit. The frequencies depend on the utility or cost functions that the individuals consider for the decision-making; these functions involve attributes of the set of candidate choices (i.e. technology cost, energy efficiency and performance), as well as features specific to the class of the representative decision-maker (i.e. easiness of substitution).

The above formulations require non-linear programming functions (i.e. Logit, CES[15], Weibull) that are currently used in large-scale energy system models including PRIMES. However, in the ESDS tool, we decided to linearize these functions in order to:

- Ensure faster runs of the backend ESDS energy demand and supply model; fast running times are particularly important for an online tool aiming to facilitate web-based user interactions and ensure its high usability by relevant stakeholders
- Ensure no numerical problems when obtaining the optimal model-based solution. It is common that non-linear functions create numerical problems, especially in cases of large computational models.
- Maintain the features and behaviour of the non-linear functions that capture energy system dynamics and consumer behaviours more accurately than linear programming formulations.

The linearization of energy demand functions has been implemented through the Koopmans activity approach. In particular, the backend ESDS model includes CES functions forming a decision tree but with only two nodes in each step. Using the first-degree Taylor expansion of the CES function at a given point to define the equation of a

[15] Constant Elasticity of Substitution

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tangent of the isoquant, we linearise the CES functions drawing 10 tandems at different points of the CES function.

3.4 Energy supply modules

The energy supply modules of ESDS simulate the future developments in the sectors supplying energy carriers to the consumers. The energy supply sectors included in the backend ESDS model are: power generation, refineries, and production of new clean fuels, including hydrogen and clean synthetic gases produced from RES-based electricity. In each energy supply sector, the ESDS model assumes that agents aim to optimise their total production costs up to 2070, including both capital (CAPEX) and operational expenditures (OPEX) as well as CO_2 costs, subject to several constraints, including:

- Demand for energy carriers by final consumers
- Dynamics of technology and equipment vintages
- Power-system constraints (including reserve margin, ancillary services, flexibility requirements, ramping of power plants)
- Potentials and constraints of specific technologies, fuels, resource types etc.
- Substitution possibilities between technologies and fuels
- Exogenous investment and decommissioning of old power plants
- Energy and climate policies and targets, user-defined policy measures

The section below focuses largely on the representation of the power generation sector, as it is one of the key pillars towards decarbonisation of the EU energy system and is projected to play a key role in the low-carbon transition, induced by:

- Decarbonisation of the power supply mix, driven by EU-wide ETS carbon pricing and RES-support policies in EU Member States. Several low-carbon technologies (i.e. solar PV, wind) are already competitive with fossil fuel-fired thermal power plants and will be massively deployed if climate policy ambition accelerates further leading to decarbonised electricity supply by or before mid-century.
- Electrification of final energy uses, both in heating and in mobility uses, should be combined with the provision of sufficiently decarbonised electricity.
- The production of hydrogen and clean synthetic fuels (that would be required in deep decarbonisation context) requires large amounts of RES-based electricity. In this way, zero-emission electricity can be used to indirectly decarbonise the hard-to-abate sectors (i.e. energy intensive industries, freight trucks etc).

The ESDS electricity supply module simulates power generation by distinct technologies (operation of the electricity system) as well as relevant investments in power plants thus representing system capacity expansion. The module optimises capacity expansion and system operation simultaneously in the period 2020 to 2070. Power market simulation is simultaneous with the simulation of steam/heat market so as to capture interactions, trade-offs and synergies between cogeneration and boilers, between CHP[16] and pure-electric plants and between self-production, district heating and distribution of steam/heat.

[16] Combined Heat and Power

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The electricity supply module includes a wide range of power plant types (about 20 categories), which are represented by specific technology characteristics related to costs (split into investment, operating and maintenance and fuel costs), potentials and constraints and technical features (i.e. efficiency, ramp-up, ramp-down, dispatching, minimum operating level, capacity factors, flexibility). The modelling also includes investment in various types of electricity storage. Load duration curves are estimated based on the characteristics of the different electricity consumption sectors in each country (i.e. industrial sectors, households, transport, services), while plant dispatching is endogenous in the model. Non-linear cost-supply curves are included in the model, both for fossil fuels and Renewable Energy Sources (RES), while grids are implicitly represented thought T&D[17] costs and grid tariffs. The model can reliably quantify the impacts of explicit energy and climate policy measures, including ETS pricing, efficiency policies, energy taxation, RES promoting measures, FITs and phase-out policies in various EU Member States (i.e. related to coal or nuclear phase-out). The model also includes decommissioning of old power plants as well as investment in new plants (either exogenously specified by the user of the ESDS tool or endogenously based on cost optimisation).The following power plant categories are included in ESDS:

Power plant types	
Nuclear	Biomass-fired
Solar PV	Biomass-fired district heating CHP
Wind onshore	Biomass-fired industrial CHP
Wind offshore	Hydropower plant
Peak device plant	Fossil fuel-fired district heating CHP
Solids-fired plant	Biomass-fired CCS plant
Combined cycle gas (CCGT)	Solids-fired CCS plant
Fossil fuel-fired industrial CHP	Gas-fired CCS plant
Other RES plant	Electricity storage plant

Table 1: Power plant categories included in ESDS

A power plant technology is characterized by the following attributes:

- Fuel and technology used
- Heat rate (inverse efficiency ratios)
- Operational features (gross and net capacity, ramping rates, technical minimum, minimum up and downtime, maximum contribution to each type of ancillary service)
- Age (commissioning date, date of planned decommissioning)
- Costs (capital cost, fixed O&M cost, variable operating cost, fuel cost)
- Environmental features (carbon dioxide emissions).

The ESDS supply module accounts for the variability in load/electricity consumption and in the production of variable RES (wind, solar PV). The model includes 14 typical hours per year in order to represent the variability of the load and intermittent RES production. The time resolution of the ESDS aims to capture seasonal, daily and hourly variability and periods with very high (or low) load and high (or low) production from variable RES due to weather conditions. The selected time resolution serves two main purposes:

[17] Transmission and Distribution

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- to better represent the specificities of the power system of EU countries, especially in the context of high deployment of variable RES
- to achieve short running time of the backend model, which is critical to ensure maximum usability of the online tool by various users (policy makers, businesses, stakeholders, researchers).

The fully endogenous investment and plant operation modelling covers all known power generation technologies (about 20 technologies are represented separately) with a detailed representation of renewable energy sources. Daily and seasonal variations in electricity consumption and renewable energy production are captured through hourly modelling of several typical days for each year. The model incorporates feed-in tariffs and other supporting schemes for renewables and simulates investment behaviour in RES following project-financing considerations. The ESDS includes reliability and reserve constraints, such as reserve margin constraints to address forced outages of plants or unforeseen demand increases. Ramping up and ramping down restrictions of power plant operation, balancing and reserve requirements for intermittent renewables and reliability restrictions on flows over interconnectors are also included. Flexibility to balance intermittency from renewables is ensured by storage (various storage options are included), ramping possibilities of power plants (which influence technology mix) and demand response.

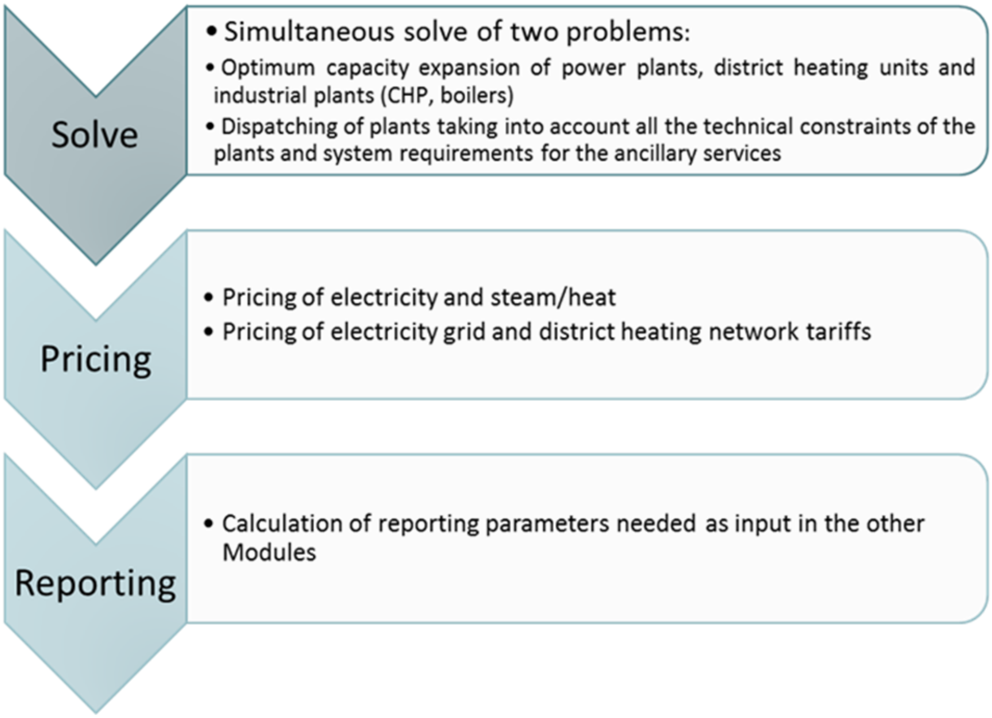

Figure 2: Schematic representation of the ESDS power supply module

Transmission and distribution networks are taken into account implicitly with the respective loss rate and costs/grid tariffs. The backend ESDS model represents interactions with neighbouring countries, in the form of imports and exports of electricity (which are defined by the user of the online tool). The model decides endogenously on investment in new power plants to meet electricity demand and system reserve requirements, while old plants are decommissioned due to their age. The user can define

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exogenously the decommissioning of old power plants as well as investments in specific power plants in each EU country (for example to represent investment in power plants that have already been implemented or are currently in the construction stage).

A novel feature in the ESDS is the inclusion of non-linear cost-supply curves for all types of fuels, as well as for renewable power sources, for CCS and for nuclear plant sites. These cost-supply curves are numerical functions with increasing slopes serving to capture take-or-pay contracts for fuels, possible promotion of domestically produced fuels, fuel supply response (increasing prices) to increased fuel demand by the power sector, exhaustion of renewable energy potential (i.e. for PV, wind and hydro plants), difficulties to develop CO_2 storage areas, acceptability and policies regarding nuclear site development, etc. The non-linear cost-supply curves are fully included in the optimisation of capacity expansion and operation of the electricity system in the backend model. The ESDS power supply module finds technology and fuel mix by minimising total system costs over the period 2020-2070, taking into account resource availability constraints (i.e. due to potential fuel exhaustion, site availability restrictions, limitations in renewable energy expansion) as well as a broad spectrum of energy and climate policies.

The ESDS backend modelling simulates the operation of a wholesale electricity market[18] in each EU country. The optimisation problem is the minimisation of total system costs, including the annualised capital costs of investments and all variable and fixed costs for the Operation and Maintenance of power plants to meet the electricity demand in each time segment (by industries, households, services and transport), trade with neighbouring countries and T&D losses. The optimisation is subject to several constraints regarding plant and system operation, capacity expansion and potential limitations by fuel and plant type as well as policy constraints and targets.

The backend modelling ensures that electricity supply satisfies electricity demand in each time segment of all years in all EU countries, while balancing in heat and steam markets is also ensured. The model considers given levels of reserves both for the capacity expansion and system operation problems. Each power plant is assumed to preserve part of its capacity to deliver a minimum level of ancillary services, which is specified by the online user. The power system modelling decided on additional capacity investments so as to meet the system reserve margin (specified by the user). The model does not represent possible electricity network constraints.

Plant-related constraints are used to define the optimal operation of electricity system and include: reserve requirements, maximum operating hours, technical minimum, ramp-up and ramp-down rates and minimum uptime and downtime[19]. All these technical

[18] The emergence of prosumers and decentralised RES-based generation in many EU countries may lead to changes in wholesale electricity markets; these changes can be large especially in decarbonisation scenarios with increased uptake of prosumers. This is considered in the backend modelling in a simplified manner, as the uptake of prosumers impacts on residual load and conventional centralised power plants and storage needs in EU countries. The representation of prosumers will be further improved in the final ESDS version to capture in detail issues like the optimal use of PV/battery-self consumption and demand response, the value of decentral electricity generation in the retail markets, the behaviour of prosumers etc.

[19] Ramp-up rate: the rate of power increase of an already started-up unit, Ramp-down rate: the rate of power decrease of an already started-up unit, Minimum uptime: the minimum operating hours of a started-up unit, including ramp-ups and ramp-downs, Minimum downtime: it incorporates minimum synchronization and desynchronization times into one parameter

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characteristics of power plants can be modified by the user, but within pre-specified ranges representing specific technology features. The ramping constraints indicate the rate at which the power plants should increase/decrease their output to meet the electricity demand in each time segment. In addition, the operating units cannot be shut down before a minimum time passes (minimum uptime) while the non-operating units cannot be started up before a minimum time passes (minimum downtime).

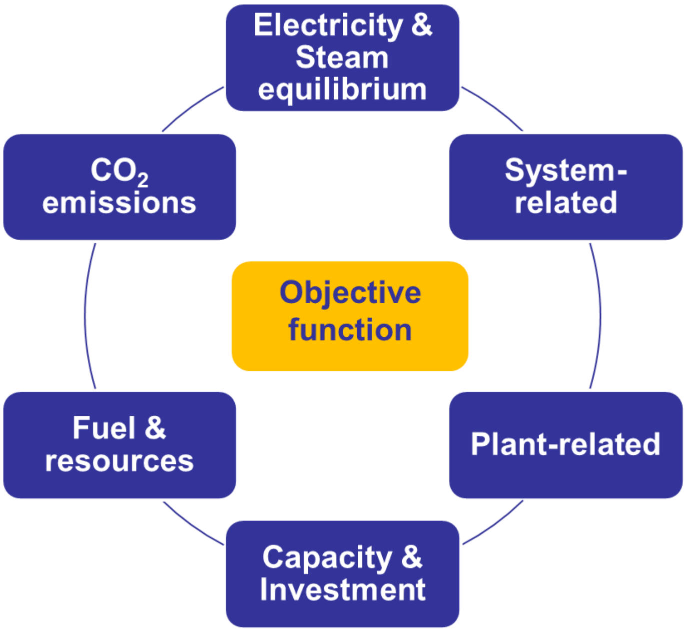

Figure 3: Graphical representation of the ESDS power supply module and the constraints

Each power plant cannot offer more capacity to meet ancillary services than indicated in its technical characteristics (which can be modified by the user of the online tool but always within prespecified ranges). The power generation plus the provision of upward ancillary services of each plant should be equal to the maximum power that these units can generate (full capacity multiplied by the capacity factor). For thermal power plants (based on fossil fuels, biomass or nuclear energy), the capacity factor is considered to be close to 1. For RES technologies (especially PV, wind onshore and offshore), the capacity factor in each hour is calculated based on the hourly pattern of variable RES generation. In addition, electricity generation of a unit should not exceed the power generation of this unit if operated for the maximum operating hours according to its technical features. A power plant operates between a minimum and maximum power output and its ramping is also constrained by ramping limits. In addition, power generation minus the downward ancillary services of each unit should be always (every time segment) greater than the technical minimum output of the unit.

The backend ESDS power supply module decides on capacity investments in power plants and storage capacities endogenously in order to: meet the future electricity and steam demand in each time segment, keep adequate reserve margin, comply with all system and plant operation requirements and replace decommissioned power plants. The web user of the tool can define exogenously investment in new power plants (i.e. in case

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that there are plants under construction or plants whose license is issued and the year of commissioning is known with certainty). Investment constraints reflect the possibly limited potential on investing in some plant types (i.e. nuclear plants, RES) and are given exogenously by the ESDS user. In addition, the backend model accounts for the relative difficulty in developing incremental capacity, which is modelled through non-linear cost-quantity curves. Cost-supply curves are numerical functions with increasing slopes serving to capture the possible promotion of domestic fuels, exhaustion of renewable energy potential, CO_2 storage limitations and policies and acceptability regarding nuclear site development. As the backend ESDS is a linear energy system modelling tool, non-linear cost-supply curves are represented by stepwise linearized functions with increasing slopes. The potential of a fuel resource or the investment in new capacity for power plants is divided in 5 discrete levels representing e.g. increasing costs when potential sites for RES and nuclear are exhausted in a specific country. The fuel price or capital cost is multiplied by a parameter which increases by level to reflect the increasing difficulty to perform new investment (these can be modified by the user). The non-linear curves affect the decisions for investment, operation and fuel consumption in power plants; however, they do not affect the end-user price of electricity, which is calculated upon actual prices and costs. The capacity of a plant type in each level of the cost-supply curve in each year should not exceed the cumulative capacity potential per type, level and year. In the non-linear cost-supply curve applied to renewable energy sources and nuclear, higher levels correspond to higher investment costs; for fossil fuel-fired power plants, the fuel consumption by level should not exceed the maximum quantity of fuel per level of cost-supply curve, while higher levels correspond to higher fuel prices.

The ESDS power supply module calculates fuel consumption in each power technology and time segment as a linear function of the electricity generation, multiplied by the heat rate value defined exogenously by the user for each fuel and plant type. To calculate the resulting carbon dioxide (CO_2) emissions from power generation, ESDS multiplies fuel consumption (coal, oil, gas) with the respective emission factor by fuel, differentiating between plants with and without Carbon Capture and Storage (CCS). The ESDS Supply Module enables the online user to assess, through the design and development of multiple scenarios, the effect of alternative energy and climate policy measures and targets (i.e. for energy efficiency, RES development and CO_2 emissions reduction).

3.5 Pricing and Balancing

The ESDS includes a detailed balancing and pricing backend module, with the objective to ensure balance and equilibrium between energy demand and supply for all fuels and energy carriers in each time segment, sector and at the country level. Market equilibrium is ensured in each sector, with market-derived prices for energy carriers (electricity, gas, hydrogen, steam) emerging through iterations between energy demand and supply. The price for each energy carrier is calculated based on the evolution of average generation costs (including both capital and operating expenditures), policy-related costs (e.g. related to energy taxation or emission regulations) and costs for transmission and distribution.

In the backend ESDS model, energy consumers maximize their utility or minimize costs under budget and activity constraints to determine the energy consumption, energy mix and use of specific energy carriers in relation to other spending, not related to energy. For

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this choice, energy consumers and producers consider explicit or shadow carbon prices (for ETS and non-ETS sectors respectively) as well as shadow values related to the achievement of potential RES and energy efficiency targets (that are imposed by the tool users). Energy consumers are assumed to be price-takers in energy and carbon markets. The pricing modules of the backend ESDS tool calculate supply costs by sector and determine prices for energy products by sector based on total production costs. A market balancing routine ensures demand and supply equilibrium in all markets simultaneously, and determines market clearing prices, after iterations involving all the modules.

Producers of energy products and carriers minimise their costs to meet demand for energy and determine the optimal mix of energy inputs (i.e. how much gas or wind is used for power generation) taking into account the cost-supply curves for fossil fuels and non-fossil energy sources and the engineering, plant and system constraints (i.e. ramp-up and ramp-down, reserves, flexibility requirements). Based on costs and market conditions, the ESDS modelling determines prices and tariffs for energy carriers differentiated by type of consumer (i.e. industries, households, transport). Overall constraints on carbon emissions, renewables and energy efficiency may apply (as specified by the online user of the tool), conveying shadow values to both energy consumers and producers. All energy consumption and production decisions are dynamic, usually assuming foresight, and technological choices are tracked by vintage with features evolving dynamically.

Following the market equilibrium between electricity demand and supply in each time segment and year, the backend ESDS model simulates wholesale markets and electricity tariffs are estimated based on the average cost of electricity generation, transmission and distribution (which may differentiate by consumer type). The pricing approach adopted in ESDS tool allows for the calculation of different end-user tariffs by sector according to the load profile of each end-user category. Most industrial sectors are associated with an almost stable annual operation, without large demand peaks, served by mainly base-load plants (with cheaper costs per unit of electricity produced), while the load profile of households in EU countries is less smooth throughout the year with occasional peaks, served by both base load and peaking plants (which are commonly more expensive).

3.6 Representation of disruptive mitigation options

The backend ESDS modelling tool has been designed to provide long term energy system projections and system restructuring up to 2050 and 2070. The ESDS projections include energy system balances, fuel and technology mix by sector, structure of power system and other fuel supplies, investment and technology uptake, costs by sector, overall energy system costs, consumer prices, carbon costs and investment requirements by sector.

The backend model cannot produce short-term projections as it is not an econometric tool based on past observations. In contrast, the modelling tool is designed to produce medium and long-term projections for energy system development and is well-suited to simulate long-term structural changes at the sector and system level, as a result of its robust micro-economic foundations. The backend model represents all energy demand and supply sectors in separate modules with endogenous representation of technology learning and innovation for a wide spectrum of electricity, energy and transport technologies. The structural micro-economic formulation of the backend model embeds engineering details and technical restrictions in the economic, behavioral optimization problem.

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In this modelling context, technological change can be driven by economies of scale and learning-by-doing, while disruptive technological breaks are explicitly represented. To simulate long-term, disruptive structural transitions, the backend model is fully equipped with a set of innovative clean energy options, including green hydrogen and clean synthetic fuels produced from RES-based electricity, deep electrification of energy uses, storage of electricity, Negative Emission Technologies (i.e. Biomass with CCS, Direct Air Capture) and Carbon Capture, Use and Storage (CCUS). The disruptive mitigation options and technologies are fully embedded in the modelling approach towards market equilibrium. These disruptive technological options are required for the development of deep decarbonisation pathways, especially those targeting climate neutrality. The uptake of disruptive options can be increased by the user of the online tool by modifying the values of relevant parameters (i.e. costs or social acceptance of hydrogen) or the intensity of climate policy measures towards the energy system decarbonisation.

4 Typical inputs and outputs/Data sources

4.1 Model inputs and outputs

The section below presents the main inputs included in the ESDS as well as the key output emerging from the online tool projections for the period to 2050 and to 2070. As the ESDS is designed to be an integrated, online tool allowing easy, web-based interactions with the user, all model inputs and other exogenous assumptions (i.e. related to policy measures) can be modified by the online user. It should be noted that in order to facilitate and support the user in the process of modifying inputs and developing alternative scenarios, the ESDS online tool includes “benchmark” values for all input parameters in the baseline scenario (that are in line with historical and current energy system trends and the baseline trends scenarios for the EU and include recent and consistent technology data and outlooks for energy, electricity and transport technologies.

Model inputs	Model outputs
Socio-economic developments	Energy balances in 2020-2070 by five-year time steps
Sectoral activity indicators	Detailed energy demand projections by sector
World prices of fossil fuels	Transport activity, modes/means and vehicles
Technical and economic characteristics of energy technologies and equipment	Detailed balance for electricity and steam/heat, including storage and system operation
Energy consumption habits, parameters for comfort, and energy efficiency potential	Production of fuels (conventional and new fuels, including hydrogen and clean synthetic fuels)
Interest rates, risk premiums by sector, possibly differentiating by technology	Investment in power generation, technology developments, vintages
Taxes and subsidies on energy products	Power supply mix by technology and time segment
Resource potential and supply curves for renewable energy, nuclear and fossil fuels	Energy costs, prices and investment expenses per sector and overall
Energy and climate policy targets (i.e. CO_2 emissions, RES, energy efficiency)	Policy Assessment Indicators (e.g. import dependence ratio, RES ratios, efficiency ratios)
ETS carbon pricing	Deployment of CCS technologies
Phase-out policies (e.g. for nuclear or coal)	CO_2 Emissions from energy combustion by sector
Engineering, Reliability and security of supply constraints	Energy efficiency by sector and specific energy consumption of energy equipment

Table 2: Key inputs and outputs of the ESDS modelling tool

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The ESDS tool is populated with data from EUROSTAT (mostly related to the detailed energy balances in each EU country) and other studies and databases (i.e. for technology costs, RES potentials, consumption split, activity by sub-sector, fuel prices). The ESDS tool includes the most up-to-date and reliable data for the underlying backend modelling (including recent energy balances from Eurostat) as well as recent data and projections for the technical and economic characteristics of key energy, electricity and transport technologies. The online tool incorporates appropriate user-friendly functionalities to visualise model inputs and outputs, by providing various options to design graphs (i.e. line, bar, stacked line, stacked bar) and compare the inputs and outputs of two contrasting scenarios developed by the online user.

4.2 Energy technologies

The ESDS tool includes an explicit representation of technologies both on the energy demand and the supply side. The table below includes a brief overview of technologies represented in the ESDS categorised by sector.

Conventional thermal technologies	Renewables	Nuclear and CCS
Solids-fired plant	Biomass-fired power plant	Nuclear power plant
Oil-fired	Biomass-fired district heating CHP	Solids-fired plant with CCS
Fossil-fuel fired district heating CHP	Biomass-fired industrial CHP	Biomass-fired plant with CCS
Fossil-fuel fired district heating boiler	Electricity storage plant	Gas-fired with CCS
Peak device plant	Hydropower plant	Other industrial boiler
Gas combined cycle (CCGT)	Solar PV	
Fossil-fuel fired industrial CHP	Wind onshore	
Fossil-fuel fired industrial boiler	Wind offshore	
	Power to hydrogen plant	
	Other RES plant	

Table 3: Key energy technologies included in the ESDS tool

In addition to the conventional energy-related technologies, the ESDS tool includes innovative technological options, which are required for the development of deep decarbonisation pathways, especially those targeting climate neutrality for the EU countries by 2050 or 2070. These innovative technologies are: Carbon Capture Use and Storage (CCUS), production of advanced biofuels, deep electrification of mobility and heating uses, production of green hydrogen (using RES-based electricity), production of clean synthetic fuels (e-gas and e-liquid fuels), storage of electricity and negative emission technologies (i.e. Biomass gasification combined with CCS).

4.3 Key data sources

ESDS integrates a wide spectrum of recent data, both on energy balances and fuel mix (from the updated EUROSTAT and IEA databases) as well as on future development of

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technical and economic characteristics of energy, electricity and transport technologies and on specific energy and climate policy measures in each EU Member State.

The key techno-economic assumptions included in the ESDS tool underwent a rigorous and extensive consultation with industrial stakeholders in mid-2018. This is particularly important for the "newer" technologies and disruptive mitigation options which currently have limited application in the energy system and markets and are at low TRL levels - which implies high uncertainty about their future costs and performance. In order to obtain as much as possible consistent, reliable and accepted estimates of the (current and future) techno-economic features, costs and performance of energy, electricity and transport technologies, we performed a comprehensive literature-based research, the results of which then underwent an extensive consultation with a large number of stakeholders (i.e. policy makers, industrial representatives, energy practitioners)[20]. The stakeholder consultation included experts for conventional and new technologies as well as representatives of industrial associations and energy businesses. This was performed as part of the EC-funded ASSET project[21] and the technological pathways for energy technologies are fully incorporated in the ESDS online tool developed in the INNOPATHS context.

This illustrates the positive synergies developed between INNOPATHS and other EC-funded projects and initiatives in an effort to leverage and improve existing activities, avoid doubling of effort and ensure that INNOPATHS online tools (in particular the ESDS) use the most recent and consistent data on energy technologies. The current and future techno-economic features of energy technologies used in ESDS are compared with the Technology Matrix Tool developed as part of INNOPATHS WP1; most of the ESDS technology data are well within the range of technology costs included in the Technology Matrix Tool. Please note that we have not promised to ensure full consistency between the two activities, especially as the two online tools do not include exactly the same set of technologies, while ESDS incorporates more recent data developed during 2018/2019 (while TMT uses data up to 1-2 years before, as the tool was finished earlier than ESDS).

The comprehensive literature review conducted is included in (De Vita et al, 2018[22]) and focuses both on conventional technologies (related to energy supply and demand) and on new, innovative technologies that will be required in the context of deep decarbonisation and sectoral integration. The review includes data and information from various sources and organisations, including (not exhaustive list):

- International organisations, i.e. Eurostat, Platts power plant database, JRC[23], IEA-ETSAP[24]

[20] The report of the stakeholder consultation and the assumptions is available here: https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

[21] https://asset-ec.eu/

[22] De Vita, Alessia, Kielichowska, Izabela, Mandatowa, Pavla, Capros Pantelis, et al 2018. Technology pathways in decarbonisation scenarios. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf.

[23] Best Available Techniques

[24] https://iea-etsap.org/index.php/energy-technology-data/energy-supply-technologies-data

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- Literature surveys on technologies[25], focusing on new technological options and clean energy carriers (i.e. hydrogen, e-gas, e-liquid fuels)
- Industrial associations[26] (e.g. steel, chemicals, paper, cement and others)

So, the “baseline” scenario of ESDS (i.e. the basis on which the online users can develop their own scenarios) incorporates robust, reliable and validated data on the technical and economic characteristics of energy system technologies. However, it should be noted that the user is able to modify these assumptions for all technologies up to 2070; in particular for power generation technologies, the user is able to modify the features below:

- Heat rate
- Self-consumption rate
- Electricity to heat ratio
- Maximum operating hours
- Annual capacity factor
- Overnight investment cost
- Fixed O&M cost
- Variable non-fuel O&M cost
- Fuel and CO_2 cost
- Hourly pattern (for variable RES)
- Economic and technical lifetime
- Technical minimum
- Ramping rate
- Contribution to upward spinning reserve
- Contribution to upward non-spinning reserve
- Contribution to downward reserve
- Maximum duration of daily storage cycle

The values of these parameters can be modified by the user of the ESDS online tool within the ranges specified by the tool developers in order to ensure robustness and internal consistency, i.e. avoid unrealistic capacity factors for PV (higher than 50%) or values that violate the economic logic (e.g. negative technology or fuel costs). However, all data ranges are as large as possible as the objective of ESDS tool is to allow web users and stakeholders design their own scenarios and pathways, despite the potential lack of

[25] ENEA, "The potential of Power to gas", 2016,
IEA, "Technology Roadmap. Hydrogen and Fuel Cells", 2015,
E4tech, "Development of Water Electrolysis in the European Union", 2014
Power to Liquids, German Environment Agency, September 2016
Techno-economic and environmental evaluation of CO2 utilisation for fuel production, JRC, 2016
Renewable Power-to-Gas: A technological and economic review, Manuel Gotz et al., Renewable Energy, 85, 2016
Transition of Future Energy System Infrastructure; through Power-to-Gas Pathways, Azadeh Maroufmashat and Michael Fowler, Energies, 1 June 2017
The CO2 economy: review of CO2 capture and reuse technologies, Efthymia Ioanna Koytsoumpa et al., J. of Supercritical Fluids, 23-1-2017
CO2utilization developments in conversion processes, Erdogan Alper et al., Petroleum, 3, 2017

[26] Industrial associations websites and documents (CEFIC)

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realism and policy-relevance of such scenarios (as the user of the tool is responsible for the scenarios he/she develops).

Apart from the technology data and projections, other ESDS inputs can be inserted and modified by the user of the tool, i.e. GDP and sectoral activity growth, population, energy and climate policy measures (ETS, Feed-In Tariffs and premiums for RES, efficiency and CO_2 standards, phase-out policies), international energy prices, energy taxes and subsidies, electricity imports and exports, energy losses, hourly patterns of load, discount rates by agent (private and social), curtailment penalty, limitations in technology development and capacity expansion (i.e. for RES, nuclear or CCS), and many others. The "base" scenario of the ESDS tool includes values for all these input parameters, which are derived from official sources and peer-reviewed publications as much as possible. For example, population, GDP, sectoral activity and international fossil fuel prices are derived from the EC, Reference scenario 2016[27]. The same source is used to provide the "base" values for energy taxation by country, energy T&D losses and discount rates for each energy system agent. The base year values for energy demand, supply, energy prices for final consumers, electricity trade, fuel mix by sector and power supply by source are derived from the latest EUROSTAT database.

As the ESDS online tool incorporates a backend fully-fledged energy system model, the tool outputs include (among others): detailed energy balance projections in the period 2020 to 2070 in 5-year intervals, energy demand by sector, mix of fuels and energy carriers, energy supply by source, power generation investment, electricity production and capacity by technology, energy prices for fuels and energy carriers, deployment of energy-related technologies, investment requirements, details on power system operation, policy-relevant indicators and energy system costs (split into CAPEX, OPEX, carbon and fuel costs). Both the input and the output of the ESDS tool can be visualised through appropriate figures (i.e. bars, lines, stacked bars, stacked lines), while the tool offers the possibility to compare inputs and outputs of two alternative scenarios in a user-friendly manner. These functionalities are designed to facilitate the active user interactions with the online tool and enable a proper understanding of the internal mechanisms, challenges, opportunities and impacts of the energy system decarbonisation in EU countries in the medium and long term.

4.4 The Reference scenario

The ESDS online tool includes a "Base scenario" which provides "initial" values for all parameters to facilitate the online user to select appropriate values for model parameters. The values of all parameters included in the "Base scenario" reflect those include in the official EC Reference scenario (Capros et al 2016[28]). The Reference scenario is a future projection of the EU energy system based on continuation of current and historic trends- it is not a forecast. It does not predict how the EU energy, transport and climate landscape

[27] Capros P, De Vita A, Tasios N, et al. EU reference scenario 2016 – energy, transport and GHG emissions Trends to 2050. European Commission Directorate – General for Energy, Directorate – General for Climate Action and Directorate – General for Mobility and Transport; 2016

[28] Capros P, De Vita A, Tasios N, et al. EU reference scenario 2016 – energy, transport and GHG emissions Trends to 2050. European Commission Directorate – General for Energy, Directorate – General for Climate Action and Directorate – General for Mobility and Transport; 2016

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will actually change in the future, but merely provides a model-derived simulation of one of its possible future states given certain conditions. It starts from the assumption that the legally binding GHG and RES targets for 2020 will be achieved and that the policies agreed at EU and Member State level until 2018 will be implemented. Following this approach, the Reference Scenario can help inform the debate on where currently adopted policies might lead the EU and whether further policy development and increased policy ambition is needed in the medium and long-term. This update is based on the latest available statistical data from Eurostat at the time of the modelling.

The macroeconomic outlook used in the Reference Scenario provides the framework projections on how the European economy will evolve in the coming decades. The outlook is important as it offers a view of the future structure of sectors and activities of the European economy. The macroeconomic scenario builds on recent demographic and economic projections for the EU countries provided by Eurostat and the joint work of the Economic Policy Committee and the European Commission. The international prices for fossil fuels, including oil, gas and coal, are based on (Capros et al, 2016). The technology assumptions are based on a detailed review (section 4.3). The technologies considered and reviewed for the Base Scenario are divided into: Power and heat, Domestic appliances and equipment, Industry, Transport and New fuels. The recent decline in low-carbon technology costs is assumed to continue in the future based on learning-by-doing curves (especially for solar PV and wind power). The Reference Scenario builds on policies at EU and Member State level, whose implementation intensifies until 2030 and continues afterwards, assuming no additional measures after 2030. EU level policies cover those adopted in the fields of energy, transport, and climate until 2018, including the directives and regulations included in the “Clean Energy for All Europeans” package, the revised EU ETS Directive, and key transport policies such as CO2 standards for vehicles, the Directive on alternative fuels infrastructure, etc. National policies are the ones adopted as part of the National Energy and Climate Plans (NECPs) and other national plans, as well as those planned to be adopted. This includes in particular coal phase-out, nuclear related policies and subsidies (Feed-In-Tariffs) for renewable energy.

The most important parameters of the Base scenario which take initial values from the EC Reference scenario include: GDP and demographic assumptions, technology costs, energy demand by fuel in base year, power generation mix and technology capacity (in base year), prices of energy products and policy variables (base year), hourly patterns of load, loss rates by technology/country, parameters for cost-supply curves etc. These initial values of the model parameters over 2020-2070 can be modified by the online user of the ESDS tool to simulate the effects of different assumptions (e.g. on GDP evolution or technology costs) or energy and climate policy measures (e.g. carbon tax, promotion of renewable energy, coal phase-out policies etc.).

5 ESDS tool functionalities/User interactions

This section presents a short summary of the activities performed from December 2016 to March 2020 (project month 1 to 40). In addition to these activities, the present deliverable was drafted in M35-M40 of the project, presented at the Third All Partner Meeting in mid-November 2019 and submitted online at the end of November 2019 (M36 of the project) as originally scheduled. A revised version of the deliverable is submitted at the end of March 2020 as agreed with the Project Officer.

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5.1 Activities carried out/ Prototype of the tool

The first period of the ESDS tool development started in M1 of the INNOPATHS project and ended in M12 with the submission of Deliverable 3.1 "Prototype of Interactive Decarbonization Simulator". With regards to the development of the prototype, E3M has worked to create an interactive design of the ESDS tool prototype which enables the user to create alternative low-carbon transition pathways for EU countries. Starting with initial discussions on the desired features of the online tool, E3M developed initial layouts ideas and iterated on these based on further discussions with UCL, PIK and Nice & Serious. E3M is responsible to carry out the design and development of the ESDS online tool as well as the application programming interface, the visualisation and the final launch. The ESDS tool was available in an early stage of the project in order to be used in the co-design process of INNOPATHS WP3. The early version of the online tool can be found here: http://www.innopathssimulator.eu/[29]

The prototype tool consists of a compact, mathematically simple, model, which aims at enabling the user designing alternative decarbonisation scenarios for the EU and its Member States by 2050, while providing the possibility for web-based user interactions (as the users may change various exogenous assumptions). The figures below show some screenshots of the prototype version of the ESDS tool (submitted as Deliverable 3.1). The landing page provides information about the purpose of the ESDS. The user selects a country from the drop-down list including all EU-28 Member States. After the country selection, the user is directed to the Inputs section.

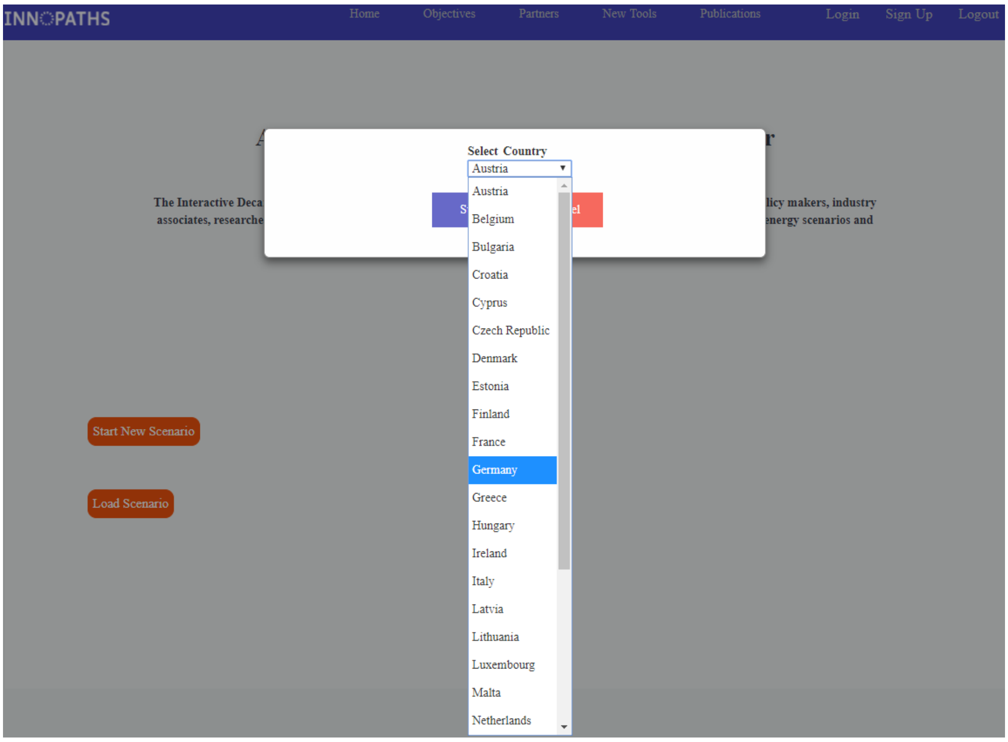

Figure 4: Landing page of the prototype online tool

[29] This prototype will be replaced by the final version of the ESDS tool.

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The Inputs section consists of ten sub-sections, namely: Macroeconomics, Energy services, Useful energy, Final efficiency, Fuel mix, Power generation, Boilers, Energy branch, Primary production and clean gas. The screenshots below display the inputs included in some of these sub-sections. Blue cells can be edited by the online user, while grey cells cannot, as they include historical data.

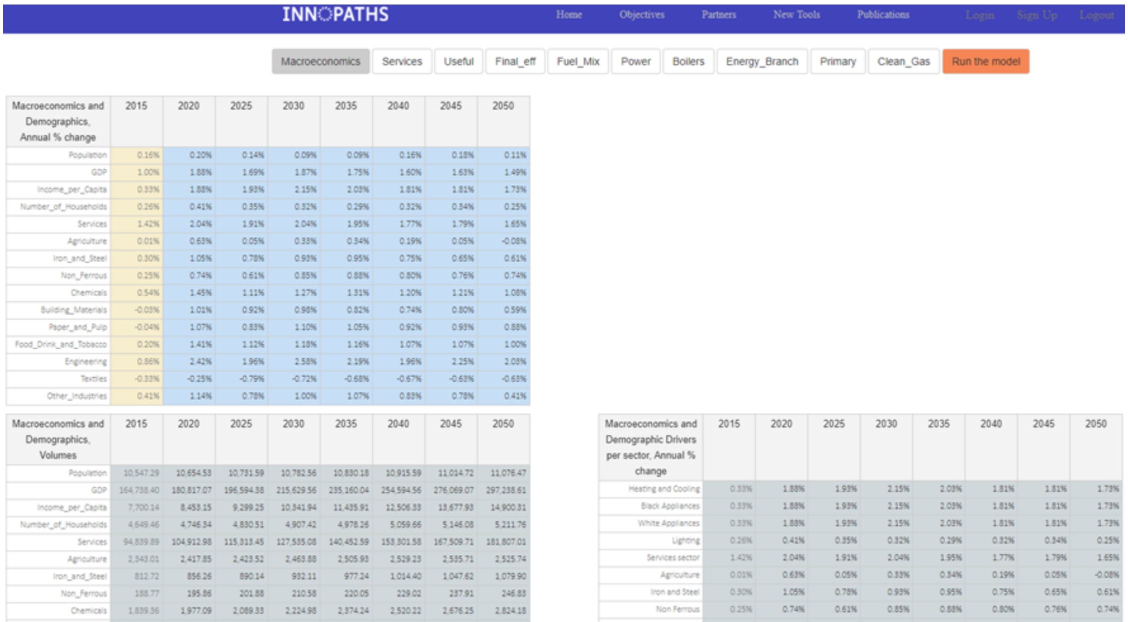

Figure 5: Macro-economic input tab of the prototype online tool

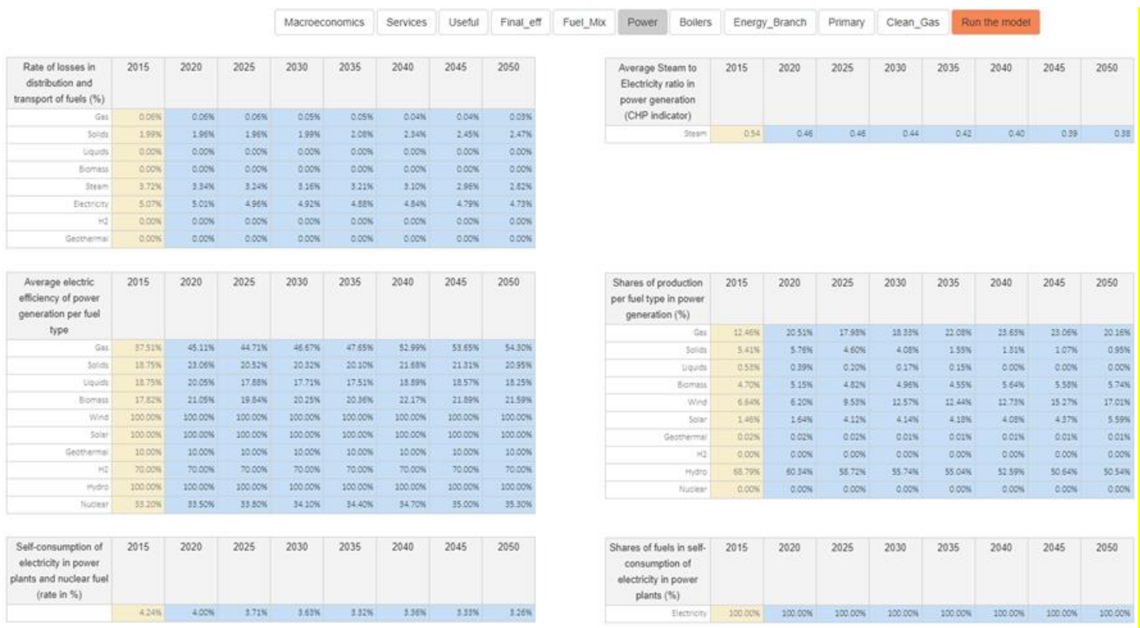

Figure 6: Power generation input tab of the prototype online tool

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After the user edits the input variables, he/she will have to run the backend model (orange button on the top right corner). It takes 5 minutes to run the backend model and calculate results.

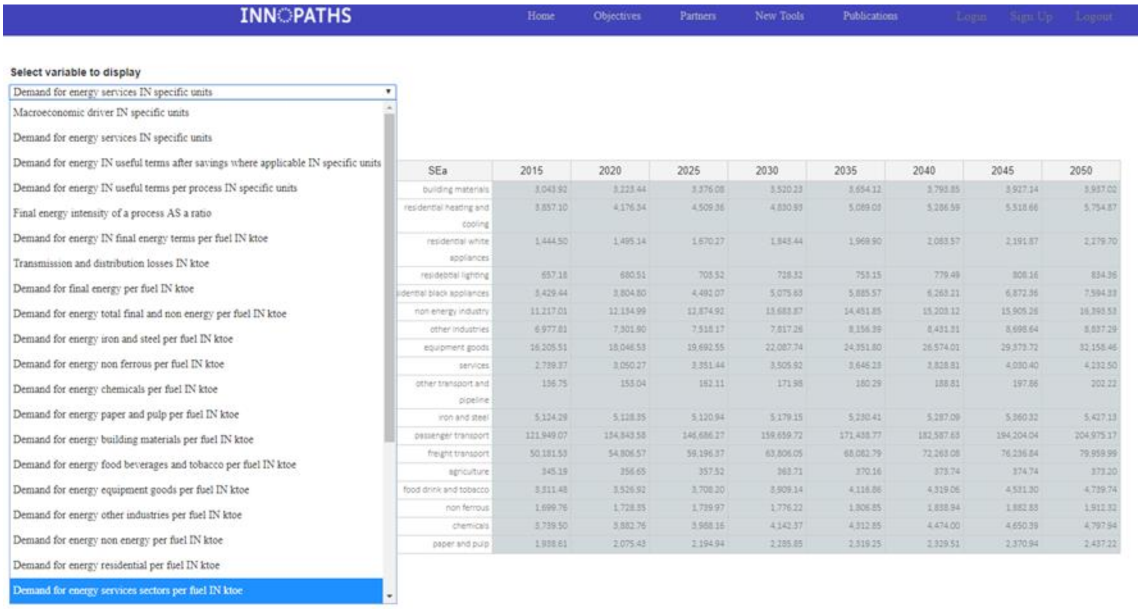

Figure 7: Output tab of the prototype online tool

The prototype of the ESDS tool was operational, but included a number of important caveats, as mentioned also in the mid-term review of the project. The deliverable D3.1 was accepted by the reviewers, but we were advised to *"consider recommendations proposed in the assessment report and take them into account in the upcoming deliverable D3.6: 'Interactive Decarbonization Simulator'*. In particular, the INNOPATHS reviewers advised us to provide further clarifications on the potential users of the tool, include additional data and describe how this tool fills a gap relative to similar online energy tools already available. So, E3M decided to move towards a radical new software approach and substantially expand and improve the online tool prototype moving beyond conventional calculators" towards a fully-fledged energy system simulator.

5.2 The current version of the ESDS tool

The improved version of the ESDS tool moves beyond simplistic conventional "energy calculators" and enables tool users to design their own low-carbon transition pathways, explore synergies, trade-offs and challenges of different mitigation options, and assess the impacts of alternative energy and climate policy instruments. In this way, the web user would understand the internal mechanisms, the difficulties and possibilities, as well as the impacts of low-carbon transition pathways on energy system evolution, technology deployment, CO_2 emissions, investment requirements and energy costs and prices. Building on the accounting framework of the prototype tool, we introduced several intelligence features (already analysed in previous sections of the deliverable) in an effort to move beyond simplistic energy tools where the user defines everything (i.e. fuel mix shares, energy efficiency achievement ratios, technology uptake) and gets the results for

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a single year. The key innovative intelligence features incorporated in the final version of the ESDS online tool are:

- Causality (the tool includes drivers of change)
- Dynamics (changes in capital stock, system inertia, technology vintages)
- Interactions between energy demand and supply and market-driven energy prices
- Representation of specific energy and climate policy instruments
- Technology learning and equipment vintages
- Integration of up-to-date data, especially on energy balances and the technical and economic features of a broad spectrum of energy, electricity and transport technologies, including innovative mitigation options required in the transition to climate neutrality (i.e. hydrogen, e-gas, CCUS, etc.)

The introduction of intelligence features in the ESDS (causality, elasticities, dynamics, capital stock, price formation etc.) and the integration of recent technology data ensure that the tool is of high-quality and provides an improved understanding of the complexities, challenges and impacts of low-carbon transition for EU countries compared to similar online tools; the latter are simplistic accounting frameworks where the user defines everything (fuel and technology mix shares, energy intensity improvements, technology deployment) and provide no clue about how much to change every share or ratio, whether it is possible to do it ambitiously without any assessment of impacts, whether it is possible in reality, which policy measures would drive such a change, etc. The naive user may falsely think that as he/she is able to change everything so easily and thus he/she can be misled to incorrect conclusions on the low-emission transition challenges and impacts. This is the main “gap” that we plan to fill with the ESDS online tool, which includes the causality, complex interactions, policy representation and structural features of a fully-fledged energy system model in a miniature size through (appropriately estimated) elasticities. The tool also includes specific energy and climate policy instruments, drives of changes, modularity and market-driven energy prices, as well as dynamics for capital stock and equipment vintages.

The desired applicability of the ESDS tool to a wide range of potential users is ensured by investing considerable effort to develop an online tool of very high quality with up-to-date data and projections, robust and rigorous backend modelling and improved user-friendly visualisation functionalities. The high quality of the online tool together with the easiness to update (periodically) and its distinguishing intelligence features compared to similar “energy calculator” tools ensure its applicability and use by a wide range of stakeholders and policy makers in the energy sector and its durability beyond the INNOPATHS lifetime. To ensure sufficient differentiation from other similar online tools, a joint workshop was held with the EUCALC H2020 research project (in May 2019 in Athens) to ensure that there is no fundamental over-lapping between the two online tools. In this way, the ESDS tool is designed to service a uniquely useful purpose among already existing tools and platforms.

Significant effort has also been devoted to improve the user-friendliness, visualisation and web presentation of the ESDS based on new software choices and include additional

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functionalities (i.e. comparison of the input and output of two scenarios). The ESDS tool includes an underlying energy systems model capturing consistently energy supply, technology dynamics and the market-driven formation of energy prices. The current online version can be found at: https://innopaths-esds.eu/; this is the permanent web address of the tool that will remain functional until the end of INNOPATHS project (and at least two years beyond this). The ESDS tool runs on a server of E3-Modelling. For the time being, users can view and modify all input data, but they do not have access to the underlying source code. The backend energy system model runs in 3-4 minutes for the EU as a whole for the period 2020 to 2070 (with parallel running and individual representation of the 27 current EU Member States plus the UK).

The ESDS tool includes the backend model code, the data and the solver in an online server of E3Modelling. The backend model was developed in GAMS and translated into Python using appropriate libraries and scripts. The online interface allows the user to modify a set of input parameters (i.e. technology costs) or policy measures (assisted by guidance-online tutorial), run the backend model online and visualise the effects on the energy system, technology uptake, CO_2 energy-related emissions and energy system costs and prices. Web-based interactions of the users with the ESDS are fully supported and facilitated by the online tool. The users have full access to all model input data, assumptions and the scenario results that they created. Multiple users are supported by the ESDS online tool (no interactions among users) which also includes appropriate visualization of model data and output through customized graphs.

5.3 User interactions with the online tool

The section describes the process of user interactions with the ESDS online tool. The landing page of the tool is: https://innopaths-esds.eu/, including a brief introduction in the ESDS tool, its objectives and core functionalities. The detailed scientific and technical background of the ESDS tool is provided in the current deliverable, which is linked to the online tool. A detailed user tutorial is close to finalisation (due to COVID-19 delays) will be added to provide adequate explanations for all steps of using the ESDS online tool. Individual users have their own accounts (that are protected by passwords) and use credentials for user authentication and profiling, but also for keeping track of their scenario runs (the process will be fully compliant with GDPR and other relevant regulations). For the time being, the credentials to users are provided by E3Modelling, via the email address: esds@e3modelling.com.

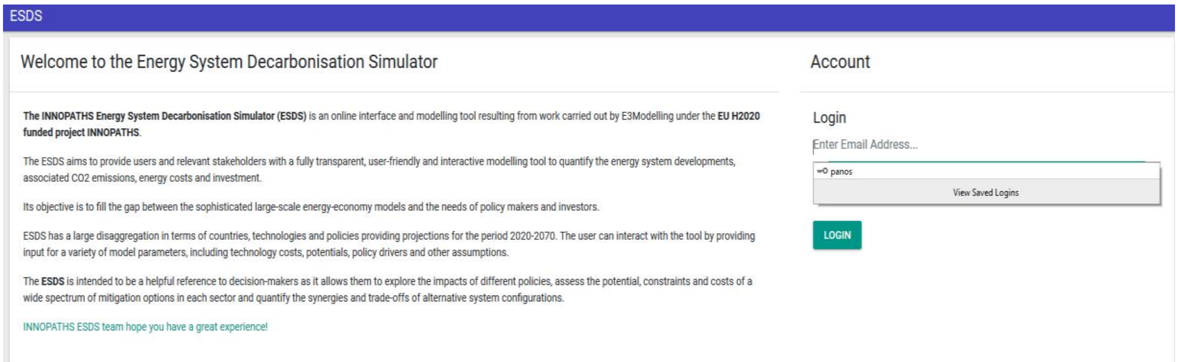

Figure 8: Landing screen of the ESDS online tool

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After entering the online tool, the user views the dashboard in the "home" tab, including an introduction to the tool functionalities and an overview of the (already performed) simulations, categorised as "currently running", "successful" and "idle".

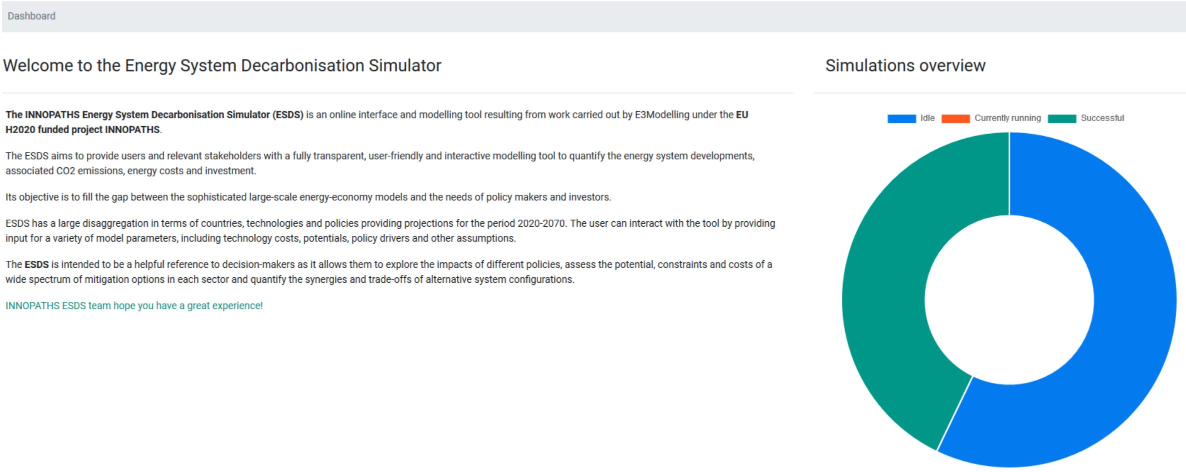

Figure 9: Home tab of the ESDS online tool

By choosing the tab "simulations" which is located in the upper-left part of the screen, the user can select either to develop a new scenario or view the results of existing or previous scenario simulations. Let's assume that the user wants to develop a new scenario. The next screen shows the key settings of the scenarios to be chosen based on user preferences. In this screen, the user should insert a name for the new scenario to simulate and (optionally) a brief description of the scenario. Two types/modes of analysis are supported by ESDS and the user can select whether he/she wants to perform the "Full scale" run (where the web user can modify more than 200 input assumptions by country) or the "Quick" scenario run (where only a subset of inputs can be modified by the user). E3-Modelling as developer of the ESDS tool suggests that the "non-expert" users should select the "Quick" scenario run, while for expert users it might be preferable to select the "Full scale" mode in order to gain an improved, in-depth and detailed understanding of decarbonization impacts on the energy system, technology uptake, CO_2 emissions and energy costs. Finally, in the "settings" screen, the user of the tool should select a scenario from a "library" of ready-made, prefabricated scenarios to start as a basis (based on which he/she may formulate new scenarios by modifying one or more data input assumptions). These scenarios are already stored in the data repository of the online tool; the data repository includes both the input assumptions and the model output of these scenarios (ensuring full internal consistency). Currently, one scenario has been uploaded in the ESDS online tool ("baseline"), which largely builds on the assumptions used in the EC Reference scenario 2016 (Capros et al 2016[30]). However, the "baseline" scenario of the ESDS tool does not reproduce exactly the energy system, CO_2 emission and energy price developments of the EC, Reference scenario 2016, as the two scenarios have been produced with different modelling frameworks. It should be noted however that the tool

[30] Capros P, De Vita A, Tasios N, et al. EU reference scenario 2016: Energy, transport and GHG emissions Trends to 2050. European Commission Directorate e General for Energy, Directorate e General for Climate Action and Directorate General for Mobility and Transport; 2016.

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provides the opportunity to the user to select as basis a scenario that he/she has previously implemented and which is saved in the online repository (and of course further modify input assumptions and/or policy measures). The different scenario versions should be stored with different names to facilitate scenario comparison by the user of the tool.

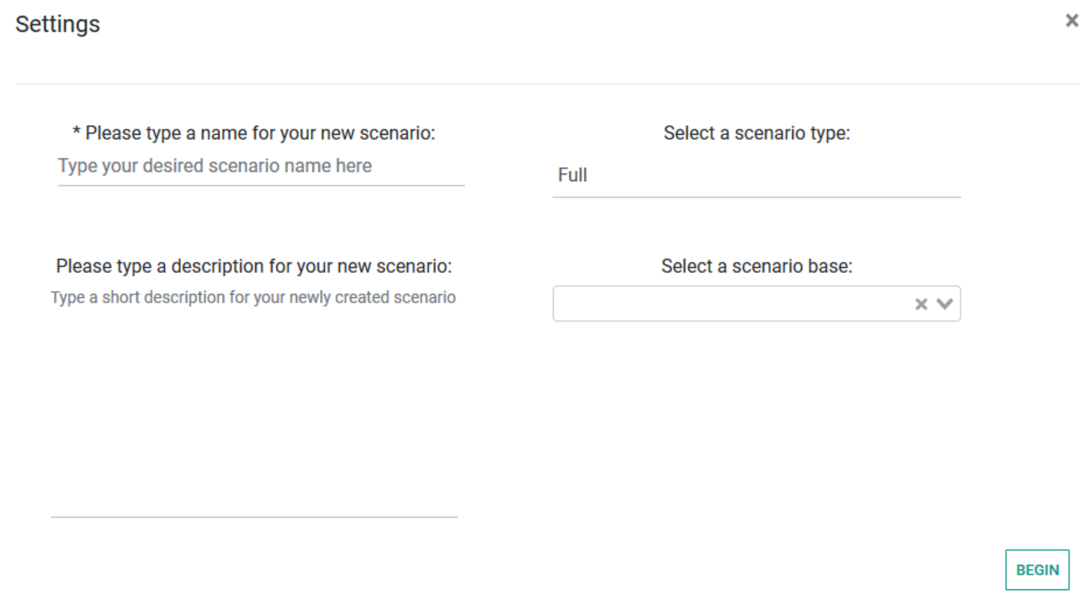

Figure 10: Screen displaying main scenario settings

When all settings have been chosen by the user, the tool opens the below dashboard including a categorization of inputs that the user may view and modify. The screen includes four columns, namely: country, topic, sub-topic, sub-topic (2). In the first column the user should choose the country to perform the analysis; all EU-28 Member States are represented individually. In the example below, the user chooses Germany.

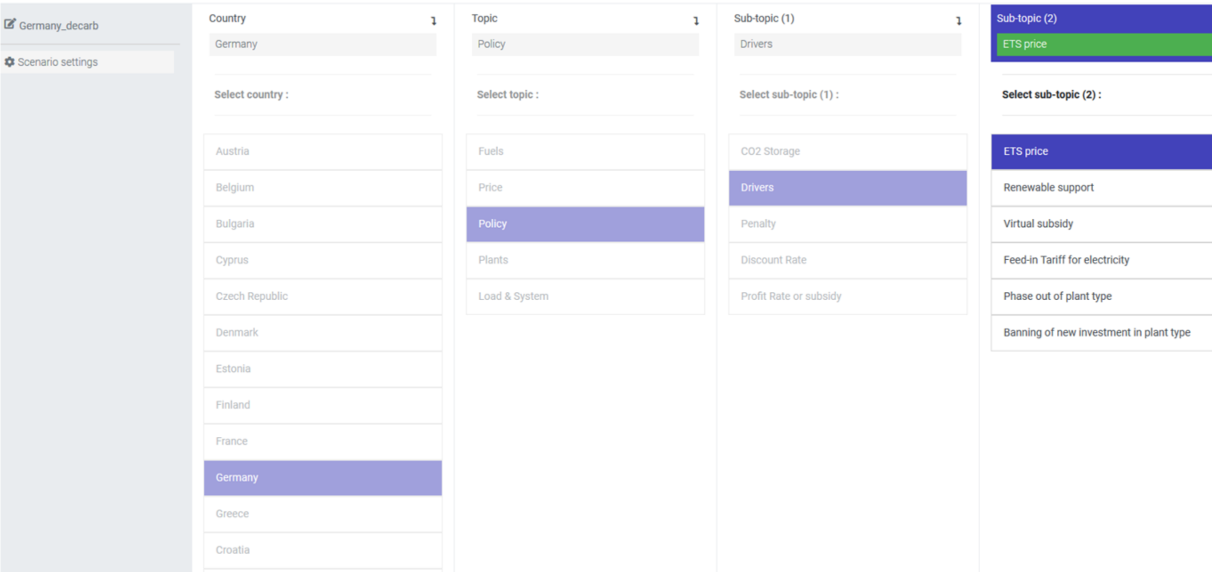

Figure 11: ESDS dashboard with categorisation of input data

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Then, the user should choose the parameter(s) the value of which he/she wants to modify. As there are hundreds of input parameters incorporated in the ESDS modelling tool, we have developed a detailed nested scheme to categorise the various inputs in order to facilitate and support the user interactions with the online tool. The user can modify input parameters via a nested scheme: going from the more aggregate categories ("topics") to the ones focusing on specific issues ("sub-topics", "sub-topics(1)"). First the user is prompted to select a "topic", among "fuels", "prices", "policies", "plants" and "load and system" (details on these categories can be found in the figure below). To ensure readability and usability of the ESDS tool, we have decided to choose simple and brief wording for the various categories of data input. In the final tool version, we also plan to include some "pop-ups" with explanations for the various data categories.

Fuels	Data on maximum potential, supply curves for fossil fuels and biomass, and fuel emission factors (with and without CCS)
Prices	Data on energy prices by sector, taxes (VAT, excise taxes), pre-tax prices and final consumer prices, grid tariffs, price indexes
Policies	Details on policy measures, like ETS price, RES support schemes, FITs, phase-out plans, subsidies, discount rates, penalties
Plants	Full techno-economic data of power plants (incl. boilers and CHP). Data on technology capacities, exogenous investment, maximum potential and cost-supply curves (for RES and nuclear)
Load & System	Details on energy demand, hourly load patterns by sector, electricity trade, losses and reserves

Figure 12: Topics included in the ESDS online tool

After the user selects a topic, then the process continues to more detailed categories (i.e. "sub-topics"). When the user selects "sub-topic (2)", then he/she should press the "input data" button (up right in the screen) that enables the user to modify the values of the chosen input parameter (for the entire period 2020-2070). For instance, if a user wants to modify the pre-tax energy prices in German industrial sectors, he/she has to select the path "Germany/ prices / pre-tax/ industry", and the tool would return the screen below:

Germany / Price / Pre-tax / Industry

Input data

Scenario base id: 5

Item EUR/kWh fuel	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
Solids	0.0092	0.0105	0.0115	0.0128	0.0138	0.0147	0.0155	0.0163	0.0169	0.0173	0.0177	0.0179
Natural gas	0.0275	0.0332	0.0356	0.0383	0.0408	0.0421	0.0431	0.0438	0.0442	0.0444	0.0446	0.0447
Oil	0.0258	0.0373	0.0414	0.0455	0.0476	0.0505	0.0519	0.0533	0.0541	0.0548	0.0552	0.0555
Biomass	0.0184	0.0213	0.0238	0.0258	0.0264	0.0259	0.0269	0.0268	0.0269	0.0270	0.0271	0.0271

Figure 13: Screen to insert data in the ESDS tool

In the upper left part of the screen, the "path" selected by the user is displayed to allow the user to check whether the correct parameter is displayed in the screen. If the user

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wants to perform a policy scenario and in particular a scenario assuming changes in the ETS carbon prices, then the path “Germany/ Policy/ Drivers/ ETS price” must be chosen and the screen displays the ETS values, as included in the EC, Reference scenario 2016.

Figure 14: Screen to insert data on ETS price in the ESDS tool

If the user wants to modify the value of ETS price in 2030, he/she should press the 2030 value and the below window opens, where the user can insert the preferable value, either by typing the number or through the slide-bar at the bottom. The original value (as in the “base” scenario) is also shown in order to enable the user to understand the magnitude of changes implemented in the new scenario. Finally, the user may choose insert the modified values for ETS prices or ignore the changes made.

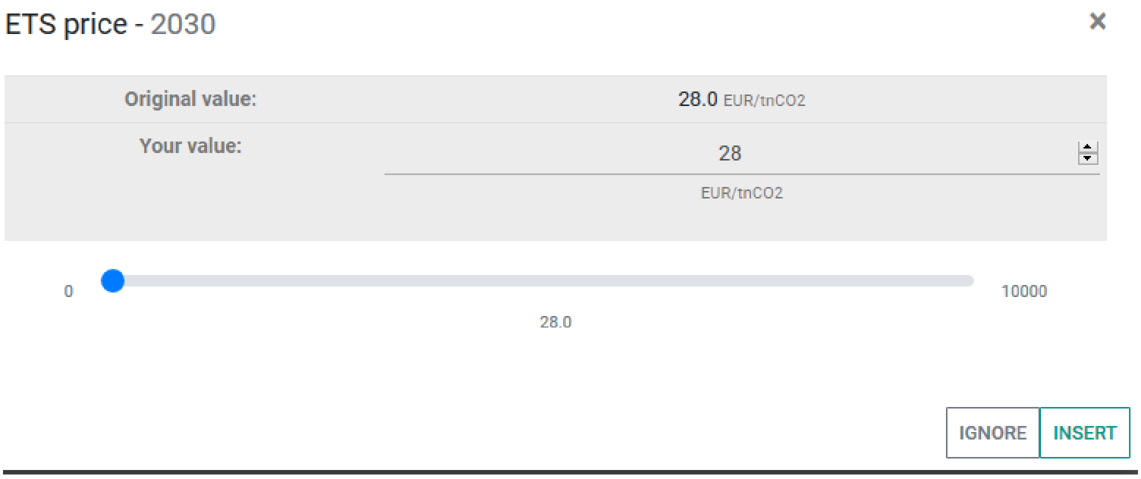

Figure 15: Screen displaying the original and modified input data

Assuming that the user chooses to modify the ETS carbon price for 2030 (from the “base” value of 28 EUR/tnCO_2 to 40 EUR/tnCO_2), the below screen is displayed, where the modified value is shown in green colour (only for the year 2030), thus notifying the user whether the required changes are implemented correctly.

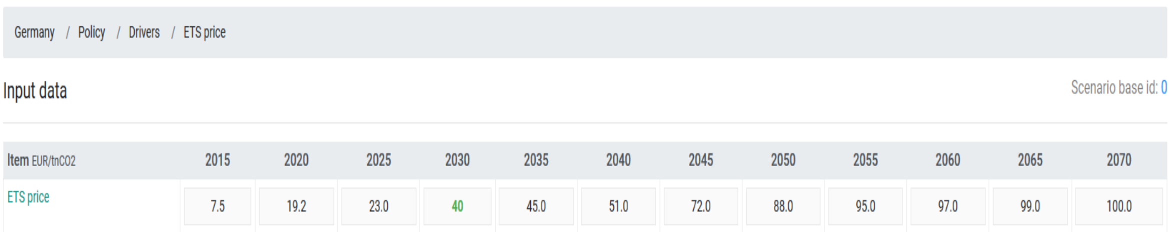

Figure 16: Data modification in the ESDS online tool

Using the “back to filters” button (displayed in the upper left side of the screen), the user may go back to the scenario setting screen, where he/she may choose to modify other

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input parameters, with the same process described above[31]. When the user has implemented all the required changes in the input assumptions, he/she should go back to the “Scenario” screen and press the “Run” Button (as in the below figure). The tool checks if the inputs provided by the user are consistent (i.e. wrong signs, missing data, unusual order of magnitude) and asks the user to correct any inconsistencies in the provided input data (before running the backend model).

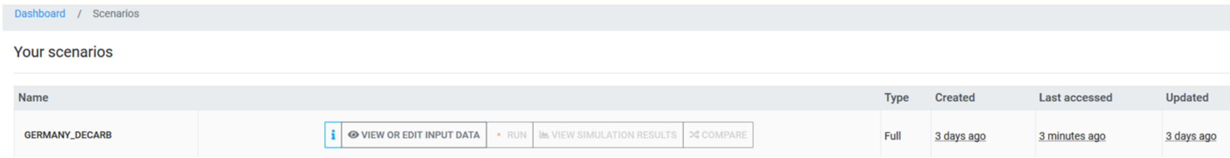

Figure 17: Scenario setting screen of the ESDS tool

The running time of the full ESDS backend model is estimated at 5 minutes to provide results for all EU-28 countries, while the power generation module requires 2-3 minutes. During the running time, the “information” tab informs the user of the running process with messages like “simulation is running”, “simulation run successful/failed”. When ESDS backend model solves and scenario results are ready, the user is notified whether the model ran successful without any errors and the tabs “View simulation results” and “Compare” are activated in the “scenario” screen. In case that the ESDS backend model did not run properly, the user gets a brief report indicating the detected inconsistencies, errors and problems. The “scenario” screen includes a list with all scenarios performed by the specific user, the type of scenario run mode (Full or Quick), the date of scenario creation and the dates when the scenario was last accessed and updated. For each scenario, the user may select one of the following:

- View or Edit input data
- Run the ESDS online model
- View Simulation results
- Compare results of two alternative scenarios

Figure 18: Scenario setting screen after a successful simulation run

When the scenario results are calculated by the backend model, the online tool can present the output in tables and visualise the results with appropriate, customised graphs. The

[31] There is also the possibility for the user to insert the entire dataset of assumptions in a batch way (i.e. as a single Excel-type table or in .csv format) The input file template is provided by the tool and would be easily downloaded and re-uploaded by the user. The file would include a comprehensive list of all inputs that can be changed by the user and their “baseline” values; the user can then select which inputs to modify in order to design the new scenario. This functionality is not yet included in the ESDS tool but can be included in the final version.

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user has full access to all model inputs and outputs of the scenarios. By choosing “view simulation results”, the user may select which variable to see and visualise. The below screen is displayed, including a categorisation of model output variables (in the same way as model input dashboard). The main difference between the two dashboards is that the output screen, apart from the country and topic/sub-topic classification, also includes tabs enabling the user to select the desired aggregation level of output variables. For example, the user may select among various aggregations to display the results related to power generation technologies, namely: “All power plants” (including 20 technologies), “power plant categories” (including broad categories like “nuclear”, “RES” and “fossil fuels”), “detailed plant categories” (including “nuclear”, “variable RES”, “CCS”, “Dispatchable RES”, “Solids/oil” and “Gas”) and “Total” (country aggregate). In addition, the ESDS online tool offers the possibility to show the results of the backend model either in annual or in 14 hourly time segments for the period 2020 to 2070.

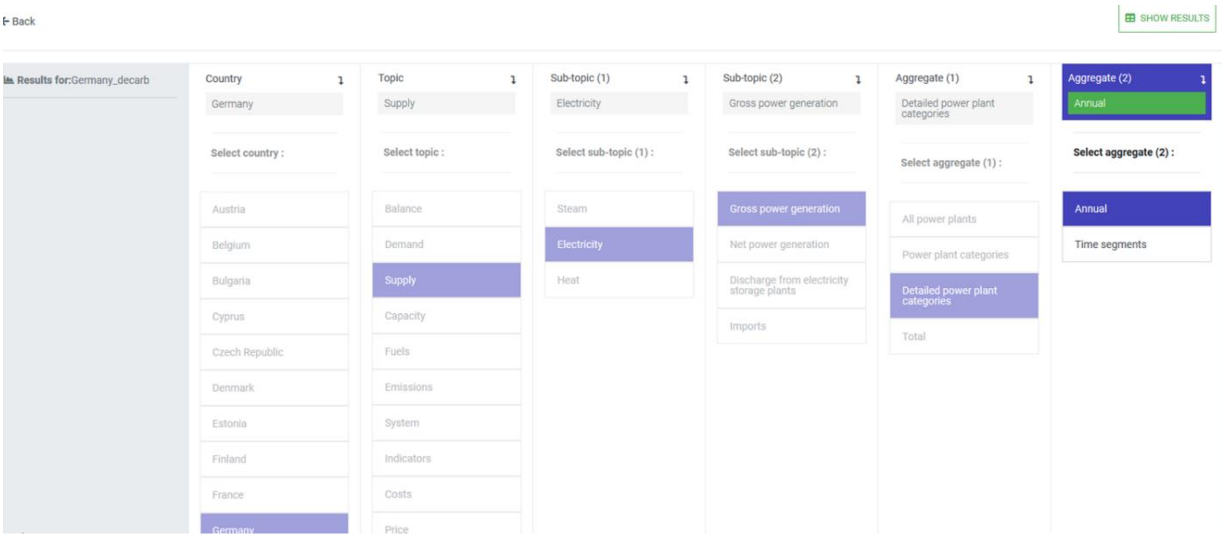

Figure 19: Screen displaying the categorisation of ESDS output

Assuming that the user wants to visualise the annual power generation mix of Germany by plant category, the following path must be followed: Germany/ Supply/ Electricity/ Gross power generation /Power plant categories/ Annual. The screen below is displayed in the ESDS web interface, including the figure and the table with detailed model output.

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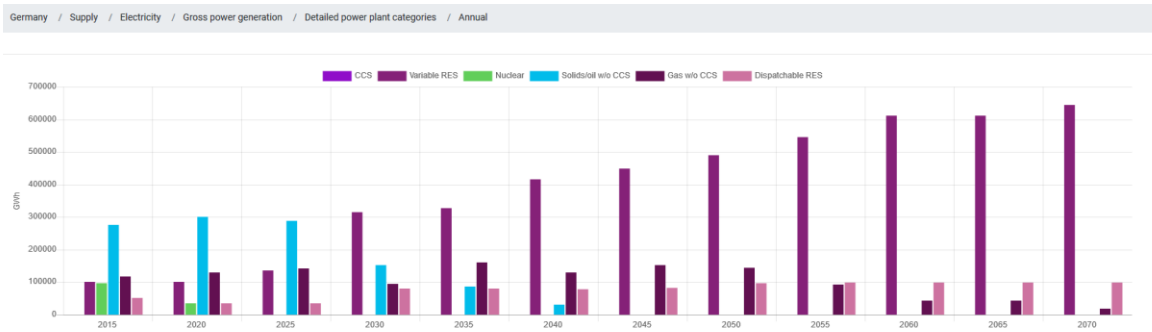
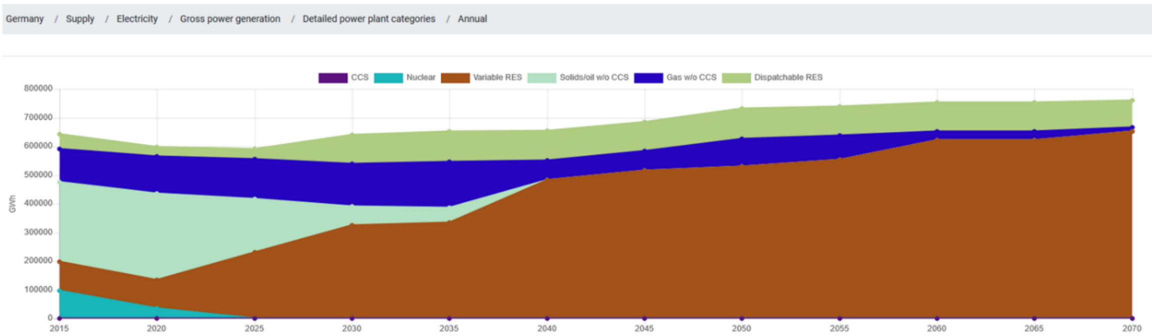


Item GWh	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
CCS	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Variable RES	100901.571366	100001.006301	135041.686697	315537.450035	327578.424862	416102.376129	449496.390180	490747.944966	545982.613172	611397.047753	644064.074623	662843.764113
Nuclear	96915.889928	34469.117376	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Solids/oil w/o CCS	276484.492730	300382.097322	287945.041364	152668.305633	85557.094594	30120.211633	358.399824	333.297161	253.968107	0.000000	0.000000	0.000000
Gas w/o CCS	116459.776976	129569.825899	142354.778557	95036.988142	160114.459529	129939.148495	151560.814909	143287.113296	93057.492274	43151.883472	18436.047989	14266.871214
Dispatchable RES	50854.399159	34072.663929	34028.422370	80008.014834	80011.127061	79093.614237	82849.111670	97071.724621	98809.512754	98933.884003	98060.592158	87749.803058

Figure 20: Projected annual gross power generation by plant type in Germany "baseline" scenario over 2015-2070

The user can select the most appropriate graph in order to visualise the different variables through the "chart settings" button, which includes four different figure types (i.e. Line Chart, Bar Chart, Stacked Line and Stacked Bar). For example, the above variable can be visualised properly with a stacked line figure (see below).



Item GWh	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
CS	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
uclear	96915.889928	34469.117376	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
ariable RES	100901.571366	100001.006301	231253.278037	324323.626455	335164.023877	481477.319739	515446.054053	528808.072632	552903.930536	621737.484759	651449.535946	662814.494397
olids/oil w/o CCS	276484.492730	300816.006840	184198.096387	66113.575013	51870.347250	210.889857	282.935511	276.568249	253.968107	0.000000	0.000000	0.000000
as w/o CCS	116459.776976	129354.439727	140595.477969	149222.050344	159598.733765	69432.614910	66760.325139	97409.291213	85126.300285	30382.070255	15568.527205	14304.143869
ispatchable RES	50854.399159	34072.836797	33915.928688	99731.269458	105864.000095	101891.743257	102747.481000	104542.174269	99711.403651	101324.092534	93063.005818	87589.932531

Figure 21: Projected annual gross power generation by plant type in Germany "baseline" scenario over 2015-2070 (stacked line graph)

It should be noted that additional options for figure types can be introduced in the online tool if requested, while colouring will be improved to ensure consistent visualisation across all figures (i.e. coal displayed with a black colour, oil displayed with a red, wind displayed with green etc). The results of each scenario run are saved (under the Scenario name introduced by the user) so that the user can view and modify them later, including the possibility of using them as new "basis" scenario. So, the web user can further modify the "saved" scenarios, but with a different name to avoid confusion. The final ESDS tool

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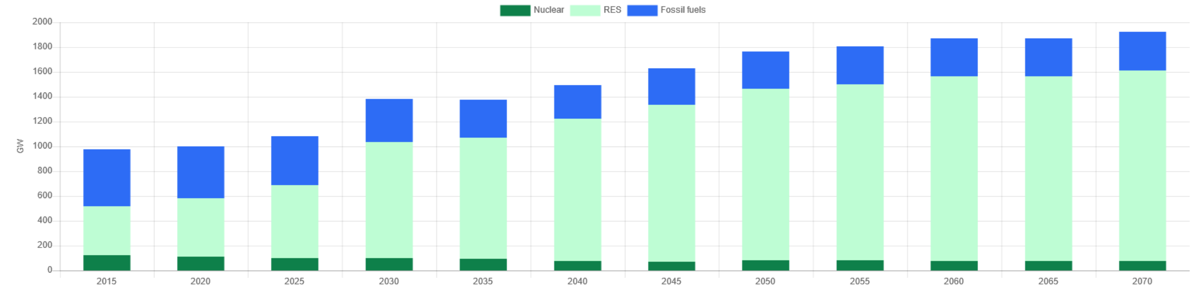
will also include the possibility for the user to download the key inputs and outputs of the scenarios he/she developed in .pdf format.

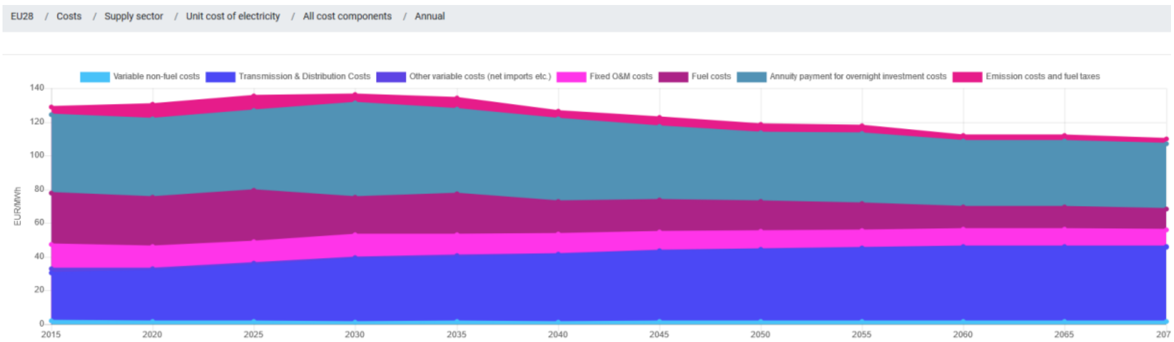
The results of the ESDS backend model are provided at the country level for each EU-28 Member State. The ESDS online tool can also calculate and display the scenario results for the EU-28 region, by appropriately aggregating the country-level results (this feature is already included in the current tool version). The figures below show some EU-28 results of the ESDS tool in the "baseline" scenario.



Item GW	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
Nuclear	120.797920	114.203760	102.215960	97.775560	95.350484	76.854134	73.429470	82.845815	80.129487	79.114215	75.500318	76.578105
RES	397.261000	469.384539	588.427404	939.546913	973.998094	1144.791242	1263.459368	1379.407654	1420.726411	1486.784428	1535.007211	1595.852891
Fossil fuels	456.974156	414.186743	389.538004	346.523723	307.927041	271.816638	291.614853	302.245005	303.150935	304.502562	313.093479	312.893555

Figure 22: Projected EU-28 power capacity in the "baseline" scenario over 2015-2070

The figure below shows the "baseline" projections for the unit cost of electricity by 2070 (average of EU-28 countries) split into its main components. The unit cost of electricity is projected to increase modestly in the period 2015 to 2030, driven mainly by the higher investment expenditures (mainly directed to RES capacities) and the increasing fossil fuel prices. However, unit cost of electricity declines after 2030 due to technology progress in RES and the reduced fuel costs (as fossil fuel-based generation is replaced by RES).



Item EUR/MWh	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
Variable non-fuel costs	2.2044	1.7225	1.7010	1.3477	1.5288	1.3883	1.5940	1.7670	1.8414	1.7737	1.7134	1.6454
Transmission & Distribution Costs	28.4198	29.9686	33.3946	37.2690	38.1806	39.6358	41.4957	42.0912	42.8575	43.8912	44.1408	44.0805
Other variable costs (net imports etc.)	2.4582	1.0560	1.2401	0.8741	0.9354	0.6563	0.5967	0.4161	0.4669	0.3737	0.2459	0.1672
Fixed O&M costs	14.3912	13.3724	12.7636	13.5547	12.6677	11.9691	11.2386	10.9826	10.5109	10.2838	9.8696	9.7783
Fuel costs	30.5331	29.0581	30.2044	22.2752	24.2330	19.0365	18.8494	17.7960	15.8251	13.4050	12.4790	11.0972
Annuity payment for overnight investment costs	46.1522	46.8983	47.7000	55.9436	50.0366	49.3814	43.6789	40.7735	41.8255	39.1602	38.6759	32.6495
Emission costs and fuel taxes	4.9159	8.2828	8.4406	4.9848	6.6757	4.4929	5.0700	4.9072	4.2723	3.2182	2.9650	2.6594

Figure 23: Evolution of EU-28 average unit cost of electricity (in EUR/MWh)

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An additional feature of the ESDS online tool is that the user can compare the input and output of two scenarios though appropriate tables and charts. To do this, the user should select the "compare" option from the initial screen demonstrating the scenario settings and select which scenarios to compare. After this step, the user may select which variable to compare and visualise in the two different scenarios. The same screen is displayed as in the "view simulation results" case, including a categorisation of model output variables and offering the possibility to the user to select the desired aggregation level to visualise the output variables and show their differences in the two scenarios.

6 Conclusions and Further work

The Energy System Decarbonisation Simulator (ESDS) online tool has been designed to provide policy makers, academics, energy stakeholders, and industrial organizations with an integrated, comprehensive, web-based and user-friendly tool for understanding, analyzing and visualizing the developments of the EU energy system in the context of low-carbon transition and climate neutrality by mid-century. The online tool provides detailed projections for energy system, fuel mix, technology deployment, CO_2 emissions, investment requirements and energy prices under various energy and climate policy scenarios up to 2050 and 2070 for each of the EU Member States.

The current version of the ESDS tool can be found at the following link: https://innopaths-esds.eu/[33] The ESDS online tool as it stands at M40 represents the deliverable outcome D3.6. "Interactive Decarbonisation Simulator" and goes beyond what was described in the research plan of the INNOPATHS project. It is suggested that the opening of the tool for full public access to be postponed till M44, by when important technicalities have been clarified and improved functionalities have been developed (e.g. an online tutorial). This will not have any influence on the progress of INNOPATHS tasks and deliverables. The ESDS online tool and the underlying code and data are now deposited at the platform web site, but a few further steps need to be clarified before the end of the project, in order to ensure the usefulness and maximise the usability and durability of the tool thereafter[34]. The tool as it stands at the date of delivery of project deliverable D3.6 (March 2020) fully meets the requirements set in the research plan of INNOPATHS and goes substantially beyond those. It is also accompanied by a detailed technical guide and documentation.

The ESDS online tool has been finalised, as the programming of the backend model, the creation of the underlying database, the design of the integrated online tool and the visualisation functionalities are finalised. The implementation and testing of the backend modelling tool have been conducted, while the focus after the joint workshop with the EU-Calc project (in May 2019 in Athens) has been mostly towards the improved visualisation and online functionalities of the tool, i.e., optimise running times of the backend model. The rights to use the data included in the tool have been obtained from all sources, as the underlying ESDS dataset is heavily based on the PRIMES energy

[33] The current version of the tool is accessible to the European Commission, INNOPATHS project partners and associated stakeholders. Anyone interested can request user credentials by E3Modelling (fragkos@e3modelling.com, info@e3modelling.com, esds@e3modelling.com) to access the ESDS tool.

[34] At the current stage (March 2020), the ESDS tool is considered finalised.

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database (which is developed, maintained and owned by E3Modeling). In addition, public data sources have been extensively used (i.e. Eurostat for energy balances and power generation capacities of EU-28 countries). It is clear that if the users of the online tool utilise scenarios and analyses developed with ESDS for academic, personal or other non-profit activities (i.e. for articles, blog entries, reports etc.), they should acknowledge the tool with the appropriate acknowledgement. However, the direct use of the tool and scenario results by external users is prohibited for business purposes.

At the INNOPATHS Work Package Leaders meeting in Athens in May 2019 and in the general partners' meeting in Potsdam in November 2019, the future prospects of the ESDS tool were discussed among INNOPATHS partners. It was concluded that a further development of the ESDS tool after the submission of the deliverable D3.6 at M40 (March 2020) would be useful to increase the life-time and usefulness of the tool, as far too often online tools fade quickly off once been launched. E3-Modelling has been responsible to carry out the design and development of the modelling tool as well as the application programming interface, the visualisation and the final launch. E3M will continue to update and improve the ESDS tool until the end of the INNOPATHS project, within its current budget frame, including: increase the clarity and easiness of using the ESDS online tool, conduct detailed review of the tool by running multiple, highly-contrasting scenarios, allow users to access, exploit, reproduce and disseminate the ESDS online tool and the underlying database, present the ESDS tool in INNOPATHS high-level final conference, in order to demonstrate the usefulness and functionalities of the online tool to the wider community (policy makers, industries, academics, business associations, NGOs, non-experts).

The final version of the tool includes all the updates, expansions and improvements discussed above. In addition, we addressed all comments received by INNOPATHS partners, reviewers, users of the tool and the European Commission. We have also linked the tool domain to the INNOPATHS project site (together with other online tools) in order to create a functional mailbox for the INNOPATHS ESDS tool to allow potential users to contact us with questions, comments or suggestions.

The ESDS online tool is produced with the highest quality allowed by the resources and we think that the tool will be useful to policy makers and other stakeholders in the energy and climate policy fields. The ESDS is developed and tested with the highest quality standards, including the underlying data, the mathematical formulation, the source code of the backend model, the web-based user interactions, scenario construction and online visualisation to ensure high applicability and usability for a wide range of potential users. The ESDS tool will remain updated (including the most recent data and statistics) at least by the end of INNOPATHS project without additional resources[35]. This time will allow INNOPATHS partners and E3Modelling enough time to improve the usability of the tool and determine what resources may be available to continue beyond that point (i.e. grant or NGO funding, new H2020 or Horizon Europe research projects). The information and data included in the ESDS online tool will require no later update (for a period of 1-2 years), only some minimal resources to keep the website alive. In case of additional funding, the online tool will be further expanded and improved with additional, more

[35] It is worth highlighting that the INNOPATHS Grant Agreement did not include the assumption that the updating of the online tools would continue indefinitely.

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advanced functionalities, improved visualisation options and with constant update of its underlying database and backend energy system modelling. We expect the ESDS tool to have a lifetime and usefulness for stakeholders (mostly policy makers and industries) of at least 2 years beyond the project itself – in case of new funding, the ESDS online tool will be further updated and improved for a longer period of time.

7 Annex

Table: Country classification of the ESDS modelling tool

	Country		Country
1	Austria	**19**	Malta
2	Belgium	**20**	Netherlands
3	Bulgaria	**21**	Poland
4	Croatia	**22**	Portugal
5	Cyprus	**23**	Romania
6	Czech Republic	**24**	Slovakia
7	Denmark	**25**	Slovenia
8	Estonia	**26**	Spain
9	Finland	**27**	Sweden
10	France	**28**	United Kingdom
11	Germany		
12	Greece		
13	Hungary		
14	Ireland		
15	Italy		
16	Latvia		
17	Lithuania		
18	Luxembourg		

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