This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Topic: LC-SC3-CC-2-2018 of the Horizon 2020 work program: *Modelling in support to the transition to a Low-Carbon Energy System in Europe*

BUILDING A LOW-CARBON, CLIMATE RESILIENT FUTURE: SECURE, CLEAN AND EFFICIENT ENERGY

Project number: *837089*

Project name: ***Sustainable Energy Transitions Laboratory***

Project acronym: SENTINEL

Start date: 01/06/2019 **Duration: 36 months**

Deliverable reference number and title:
D7.1: Case specification and scheduling

Version: 1

Due date of deliverable: 02.2021 **Actual submission date: 04.03.2021**

Dissemination Level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	
EU-RES	Classified Information: RESTREINT UE (Commission Decision 2005/444/EC)	
EU-CON	Classified Information: CONFIDENTIEL UE (Commission Decision 2005/444/EC)	
EU-SEC	Classified Information: SECRET UE (Commission Decision 2005/444/EC)	

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Please cite as:

Stavrakas, V., Ceglarz, A., Kleanthis, N., Giannakidis, G., Schibline, A., Süsser, D., Lilliestam, J., Psyrri, A., & Flamos, A. (2021). *Case specification and scheduling. Deliverable 7.1. Sustainable Energy Transitions Laboratory (SENTINEL) project*. European Commission. University of Piraeus Research Center (UPRC), Piraeus, Greece.

ACKNOWLEDGMENTS/ DISCLAIMER

The authors would like to acknowledge the support from the EC. The authors would like to thank SENTINEL colleagues for their contributions to specific sections relevant to their models and modelling themes. The authors would also like to thank the stakeholders that participated to the case study interview meetings, focus groups and thematic workshops. The content of this report is the sole responsibility of its authors and does not necessary reflect the views of the EC.

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Abbreviations & Acronyms

BECCS	Bioenergy with Carbon Capture and Storage
BESS	Battery Energy Storage System
CAES	Compressed Air Energy System
CCM	Carbon Capture and Mineralisation
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture Utilisation and Storage
CNS	Carbon Neutral Scenario
CGE	Computable General Equilibrium
CO_2	Carbon Dioxide
COVID-19	Coronavirus Disease 2019
CRES	Centre for Renewable Energy Sources
E^3MLab	Energy-Economy-Environment Modelling Laboratory
EE	Energy Efficiency
EED	Energy Efficiency Directive
EIB	European Investment Bank
EMP-E	Energy Modelling Platform for Europe
EPC	Energy Performance Contract
EROI	Energy Return on Investment
ESCO	Energy Service Company
ESR	Effort Sharing Regulation
EU	European Union
EU-ETS	European Union Emission Trading Scheme
EV	Electric Vehicle
FiP	Feed-in Premium
FiT	Feed-in Tariff
G2V	Grid-to-Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GU	Generating Unit
HGV	Heavy Good Vehicles
HVDC	High-voltage Direct Current
ICT	Information and Communication Technology
IEA	International Energy Agency
IoT	Internet-of-things
IPTO	Independent Power Transmission Operator S.A.
JRC	Joint Research Centre
KPI	Key Performance Indicator
LCA	Life-cycle Analysis
LCOE	Levelised Cost of Electricity
LULUCF	Land Use, Land-Use Change and Forestry
MEE	Greek Ministry of Environment and Energy
NECP	National Energy and Climate Plan
NERC	Nordic Energy Research Council
NETP	Nordic Energy Technology Perspectives
NDC	National Determined Contribution
NGO	Non-governmental Organisation
NH_3	Ammonia
NMVOC	Non-methane volatile organic compound

NO_x	Nitrogen Oxide
NTUA	National Technical University of Athens
NUTS	Nomenclature des Unités Territoriales Statistiques
NZEB	Nearly-zero Energy Building
OPG	Organised Prosumer Groups
P2G	Prosumer-to-Grid
P2P	Peer-to-Peer
P2X	Power-to-X
P4P	Pay-for-Performance
PCI	Project of Common Interest
PEB	Positive Energy Building
PED	Positive Energy District
PM2.5	Fine Particulate Matter
PPA	Power Purchase Agreement
PPC	Public Power Corporation S.A.
PV	Photovoltaic
RE	Renewable Electricity
RED-II	Renewable Energy Directive
RES	Renewable Energy Source
RF	Reference
ROI	Return on Investment
RQ	Research Question
SDG	Sustainable Development Goal
SENTINEL	Sustainable Energy Transitions Laboratory
SO_2	Sulphur Dioxide
TSO	Transmission System Operator
V2G	Vehicle-to-Grid
VRES	Variable Renewable Energy Source
WEE	Water-Emission-Energy
WP	Work Package
ZEB	Zero Emission Building

Executive Summary

While energy system models are important tools supporting decision- and policymakers, they are often monolithic, and, therefore, not particularly versatile and not able to address all types of problems related to the energy transition. Although models have become more complex, it does not necessarily mean that they are better suited to answer the questions asked, and address the challenges faced by decision- and policymakers. To overcome the challenges and limitations of current modelling approaches within the SENTINEL project, we will apply and validate different updated models of the SENTINEL modelling suite in three case studies of different spatial scale.

In this deliverable, we aim to **(i).** identify and specify policy-relevant scenarios, along with the respective energy targets, and qualitative narratives to base modelling runs on, and **(ii).** identify contextual critical issues and challenges in energy system planning, and specific research questions, to which the SENTINEL models will attempt to provide answers, accounting for particularities of diverge spatial scales. The main research questions of our work are: "*What scenarios should we apply in each of the SENTINEL case studies?*" and "*What are the main challenges and research questions by decision- and policymakers that the SENTINEL models should be able to answer?*"

In order to answer these questions, we applied a participatory multi-method approach in three case studies at: **a.** a National level (Greece), **b.** a Regional level (Nordic countries), and **c.** a Continental level (European Union, Iceland, Norway, Switzerland, and United Kingdom). We have selected these case studies to apply and test our models in different, heterogeneous geographical scales, as well as because of their particular policy relevant characteristics. In all three case studies, we conducted an extensive literature review to identify relevant scenarios and initial research questions. In a second stage, we engaged with a range of different stakeholders to understand main narratives underlying the scenarios as well as to identify additional research questions which energy models need to answer. In the National case study, we held bilateral expert meetings and conducted interviews, while for the Regional and the Continental case studies, we conducted two thematic online workshops. The meetings, interviews and workshops were structured in specific thematic sessions, selected from the analysis of policy documents and structured around the questions "Where we are now" (System knowledge), "Where we want to go" (Target knowledge), and "How we can go from the point where we are, to the point where we want to go" (Transformation knowledge- Transition pathways).

For each of the case studies, we identified policy-relevant scenarios and underlying narratives. For the Greek case study, we specified three scenarios, namely: **1.** "Reference" scenario, building on the trends suggesting by the recent National Energy and Climate Plan, **2.** "Renewable Electricity" scenario with the main characteristic of almost full decarbonisation of the electricity generation by 2050, and **3.** "Power-to-X" scenario which includes synthetic fuels and hydrogen to achieve climate neutrality by 2050. For the Nordic case study, we have identified the latest "Carbon Neutral Scenario". This scenario has been applied by the Nordic Energy Research Council, as a reference scenario, while further decarbonisation scenarios will be formulated based on the updated national policies of the Nordic countries. Finally, for the European level case study, we have also specified three scenarios, namely: **1.** "Reference" scenario, which corresponds to a "current trends" scenario, **2**. "Climate neutrality" scenario (linked to the European long-term strategy of climate neutrality by 2050), and **3.** "Early neutrality" scenario which assumes that neutrality occurs already by 2040.

Furthermore, for each case study, we find research questions- more than 250 questions in total- to which decision- and policymakers stated that they need answers. Under the power system transformation thematic, the recurring questions in all case studies are related to system flexibility (with demand-side flexibility considered as complementary to the supply-side flexibility), renewable electricity curtailment, and storage

options. Furthermore, irrespective to the geographical scale, interconnections are recognised to play an important role in the renewables-dominated power system. Sector coupling topics include questions on options for electrification of heating as well as infrastructure development issues and system operation questions related to the electrification of road transport. Several questions and uncertainties were noted on how Power-to-X solutions could act as an alternative to direct electrification. Industry is recognised as the hardest sector to be decarbonised in all the cases. Finally, we have identified that there is need to identify ways for achieving social acceptance for climate neutrality and ensuring a just transition.

The specifications for scenarios, narratives, and the extended list of research questions of this deliverable will inform further work under Work Package 7 and beyond within the project. More specifically, SENTINEL modellers will set-up their models by using the scenarios and assumptions for the three case studies and will conduct model-based analysis attempting to provide answers to the comprehensive list of research questions identified in this report. Applying a multi-model suite within three different case studies will allow us to compare modelling results under Work Package 8 and demonstrate the advantages of such an approach.

1. Introduction

1.1. Background

Energy system models have been a valuable tool towards well-informed decision- and policymaking processes in Europe over the past few decades (Süsser et al., 2020): they have simulated multiple energy transition scenarios and pathways, and have reflected on different possible evolutions of the energy systems (Süsser et al., In press). However, many existing modelling structures have been monolithic and unable to address the multifaced problems related to the ongoing energy transition. There are certain main challenges and limitations with existing energy system models. First, until now, energy system models have provided valuable information about how to make marginal modifications to the current system in ways that will reduce costs, and, thereby, enhance economic growth. In this context, nearly all of their details have been oriented towards the existing energy system. As a result, they were not designed to support transitions to energy systems dominated by intermittent renewables (Welsch et al., 2014).

Second, a fundamental challenge is that most of these models are very complex and, therefore, difficult to understand. To use them properly, one has to comprehend all of their elements as well as the interactions between these components. Given the additional level of detail that has come with designing an energy system based on intermittent renewables, their complexity has expanded to the point where it is extremely difficult to understand why they give the results that they do. This problem could be exacerbated even more, if one were to further develop and expand such models in order to consider other issues relevant to energy systems planning. For example, synergies and conflicts associated with sector coupling, factors limiting or enhancing public acceptance and diffusion of new technologies.

Third, most models are one-size fits-all tools. However, because they have complex structures does not automatically mean that they are better-suited to user needs (Süsser et al., In review). As we have concluded from our research under Work Package 1 (WP1), users of models and modelling results have specific needs for energy system models, which cannot be covered by "all-rounders", but by specific targeted tools (Gaschnig et al., 2020). Thus, modellers must develop tools that will address specific transition challenges in specific geographical contexts, also considering diverse spatial focus.

Considering all the points above, the Horizon 2020 EC-funded Sustainable Energy Transitions Laboratory (SENTINEL)[1] project is developing an open-source modelling platform that will try to explicitly address all critical issues of the ongoing European energy transition towards climate neutrality. To do so, the SENTINEL framework will go beyond improving the models' resolution: more fundamentally, the SENTINEL approach aims at creating an energy systems modelling framework for the 21st century. Large, difficult to maintain, monolithic models can no longer deal with the more decentralised and dynamic European energy landscape. To overcome this shortcoming, SENTINEL offers a more resilient and robust approach: it creates a system where smaller, more specialised models can be combined in a modular fashion to answer pressing questions of stakeholders.

Applying energy system models to a range of user applications, also considering stakeholders' and model users' insights and needs, is a vital step to ensure that the models work not only in theory, but also in practice. To this end, under WP7, SENTINEL includes a set of case studies at three different geographical levels (**Figure 1**): National (Greece), Regional (the Nordic region), and Continental (European Union, Norway, Switzerland,

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[1] https://sentinel.energy/

and United Kingdom), to identify the main issues and challenges of the European energy transition, which modellers and policymakers will be faced with in the future. Our rationale was to select case studies of different geographical and socioeconomic contexts, to demonstrate the applicability, and prove the ability, of the SENTINEL modelling suite, to provide answers to a variety of energy transition challenges in diverse spatial scales. Our selection was additionally motivated by their political relevance, including the leading policies of the Nordic countries towards climate neutrality, the ambitious climate targets set for the ongoing European transition, and the recent political decision in Greece to phase-out lignite by 2028.

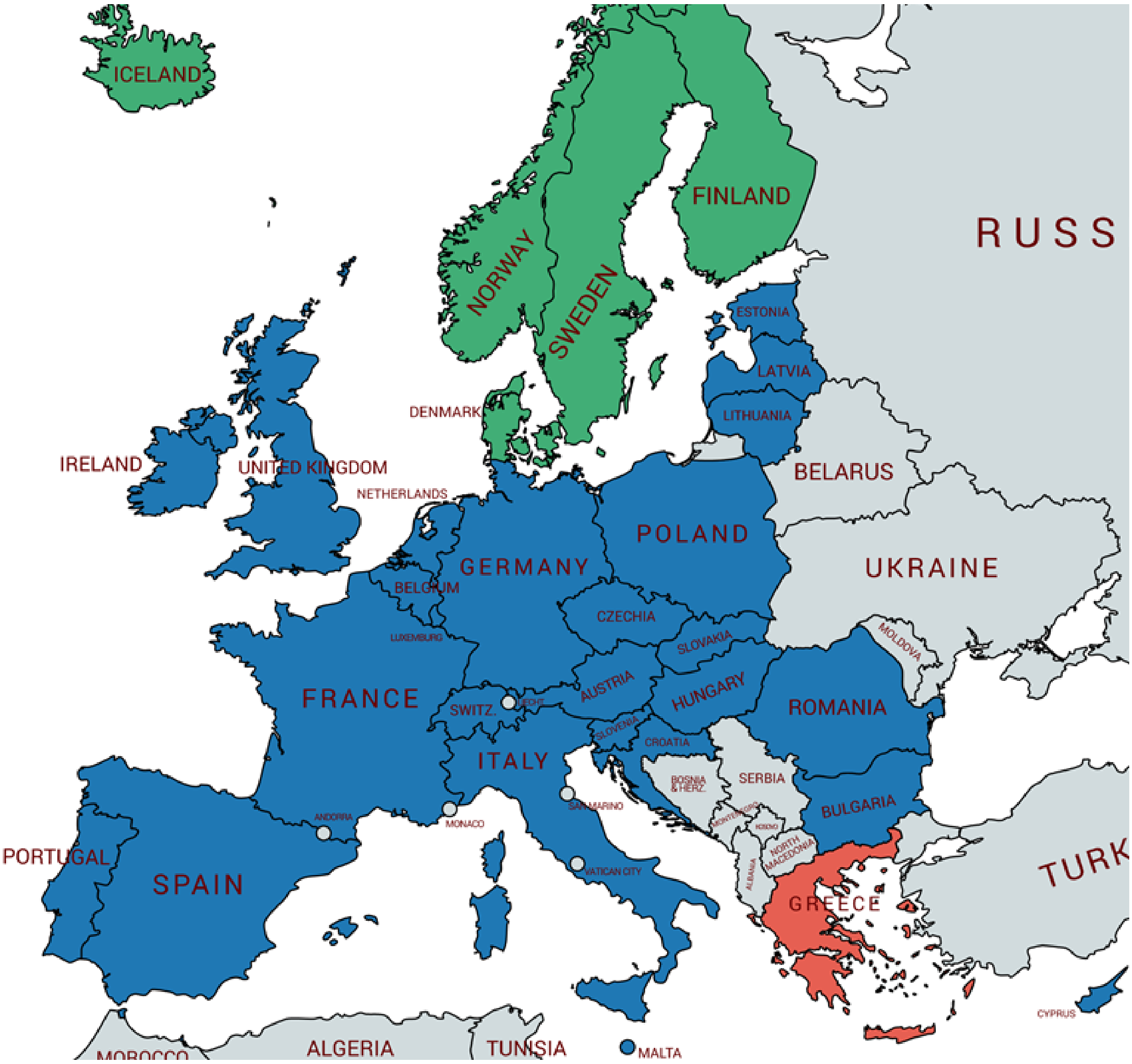

Figure 1. SENTINEL case studies: **a.** **National** level case study (Greece), **b.** **Regional** level case study (Nordic region), and **c.** **Continental** level case study (European Union, Iceland, Norway, Switzerland, and United Kingdom).

1.1.1. National level case study (Greece)

Greece is a transcontinental country with a diverse geographical landscape and a large potential in renewable energy (Vassilis Stavrakas & Flamos, 2020). It presents a very recent case of a radical change in the planning of the energy system development. Although the introduction of renewable energy was actively promoted in the energy policy agenda over the past ten years (Nikas et al., 2019), indigenous lignite continued to play a major role in the electricity generation in all scenario analysis and policies formulated until 2019. However, in the second half of 2019, the Greek government took the decision of phasing-out lignite-fired power plants in a short time horizon (by 2028). This called for an extensive modelling work to analyse its effect on the further development of the energy system. This modelling work resulted in the development of: **1.** the National Energy Climate Plan (NECP) that summarises the country's climate and energy objectives, targets, policies, and measures for the upcoming decade, also considering the European Union' relevant targets for 2030, and United Nations Development Programme's Sustainable Development Goals (SDGs), and **2.** the Long-Term Strategy towards 2050 (LTS 2050), which highlights the range of the available solutions and different scenarios for the upcoming energy transition, in the context of the long-term European energy strategy for 2050.

However, additional modelling work is required to assess if "climate-neutrality of 1.5°C", as promoted by both plans, is a feasible choice after all, maintaining the modernization and competitiveness of the national economy as key components, and creating an environment of social justice without 'winners and losers' for an energy transition with "no one being left behind."

1.1.2. Regional level case study (Nordic countries)

The **Nordic** region has been a key innovator for quite some time, both in terms of having a relatively decarbonised power sector on account of its large hydro-power resources, and because of already having taken significant steps to integrate energy markets across multiple countries (Ollila, 2017). But the Nordic countries are also taking the lead in terms of making electrification a strong energy policy priority. This is taking shape in terms of integrating heat and electricity production, including electric space heating, district heating, and the electrification of industries involving high temperature heat applications such as ammonia production and other chemical processes. It is also taking shape in the electrification of road transport, and recently even, shipping. Coupled to electrification is an emphasis on digitalisation, with the promise of optimising costs by using data management to facilitate optimal load management (Nordic Energy Research, 2019). The effort to optimise load management is also extending to the possibility of creating load centres in remote areas where generation potential is high.

All of these developments make the Nordic region an ideal testing ground for the SENTINEL platform, for two reasons. First, it presents a particularly difficult set of modelling challenges, allowing us to see whether and how the SENTINEL platform can handle these advanced optimisation tasks. Second, the innovations being pursued now in the Nordic region may well spread to other parts of Europe in the coming years, given that electrification is likely to be a necessary element of decarbonisation. Third, with its strong environmental and social policies and egalitarian societies, the Nordic region represents an interesting example to understand how to make the energy transition socially and environmentally sustainable (Nordic Energy Research, 2020).

1.1.3. Continental level case study (European Union, Iceland, Norway, Switzerland, and United Kingdom)

In the last two decades, the **European Union** (EU) has been a global leader in fighting climate change through its ambitious policies (Wurzel, Connelly, & Liefferink, 2016). Recently, this progressive approach has accelerated and at the end of 2019 European Commission announced The European Green Deal, which is a comprehensive strategy navigating the EU to become the world's first climate-neutral continent by 2050 (European Commission, 2019). The actions proposed in this document, aiming at increasing the EU's climate ambition, mobilising industry for a clean and circular economy, building and renovating in an energy and resource efficient way, and preserving and restoring ecosystems and biodiversity will lead to the complete transformation of the current energy system. Mobilising additional public and private funding and pushing investments in research and innovation, combined with multiple instruments foreseen in the recovery plan for Europe as a response to the COVID-19 crisis, will give an additional push to this transformation (European Commission, 2020f).

At the same time, the way leading to such deep transformation comprises numerous challenges and uncertainties. For more than twenty years energy system modelling has been at the heart of future European climate and energy scenarios and helped European policymakers to unpack and face those challenges (Süsser et al., 2020). However, models applied in EU policymaking have been criticised for lack of transparency and conservative assumptions (Graf & Buck, 2017). Thus, the new ambitions related to the European Green Deal require better adapted modelling tools for addressing the challenges and uncertainties of energy transition. One of their main desired features is to reflect as precisely as possible the concerns, needs and demands of stakeholders interested in, and affected by European climate and energy policies (Gaschnig et al., 2020). In this final set of scenarios, the SENTINEL modelling suite will come into play, showing that, not only do specific sets of models work together: if a future user has need for it, all elements of SENTINEL work together.

Except for EU member states, in this case study, Iceland, Norway, Switzerland, and United Kingdom are also included. Iceland and Norway have agreed on committing to binding annual greenhouse gas (GHG) emission targets for the period 2021- 2030 in accordance with the Effort Sharing Regulation. This means that they will follow the same rules and obligations, and have similar flexibilities as EU Member States so that they can achieve their targets in a fair and cost-efficient manner[2]. Switzerland shares many of the sustainable goals included in the roadmap for a sustainable economy in the EU, as presented in the context of the European Green Deal. Also, Switzerland and the EU have set largely equivalent levels of ambition in their respective energy and climate policies[3]. Furthermore, the energy and climate ambitions of the EU and UK largely converge. In fact, in a new agreement between them, the two sides highlight the stronger cooperation on energy and climate[4].

1.2. Objectives and scope of this deliverable

This report is the first out of three deliverables under WP7, and describes/ synthesises the technical, political, and social landscape in each SENTINEL case study, as a basis for providing appropriate decision-support through models. More specifically, Deliverable 7.1 aims at: **(i).** identifying and specifying policy relevant scenarios, along with the respective climate and energy targets, and qualitative narratives to base modelling runs on, and **(ii).** identifying contextual critical issues and challenges in energy system planning, and specific research questions, to which the SENTINEL models will attempt to provide answers to, accounting for particularities of diverge spatial scales. The main research questions of our work are: "*What scenarios should we apply in each of the SENTINEL case studies?*" and "*What are the main challenges and research questions by decision- and policymakers that the SENTINEL models should be able to answer?*"

To meet these objectives, we followed a participatory multi-methods approach, based on literature review and extensive stakeholder engagement. In particular, since the kick-off of WP7, stakeholder engagement activities have been at the heart of our work. We established communication channels with different stakeholders from the energy industry, the policymaking sphere, the civil society and Non-governmental Organisation (NGOs), and the field of science and research. We aimed at jointly specifying the most critical and policy

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[2] https://ec.europa.eu/clima/policies/effort/regulation_en
[3] https://www.eda.admin.ch/missions/mission-eu-brussels/en/home/key-issues/enviroment-climate.html
[4] https://ec.europa.eu/info/relations-united-kingdom/eu-uk-trade-and-cooperation-agreement_en

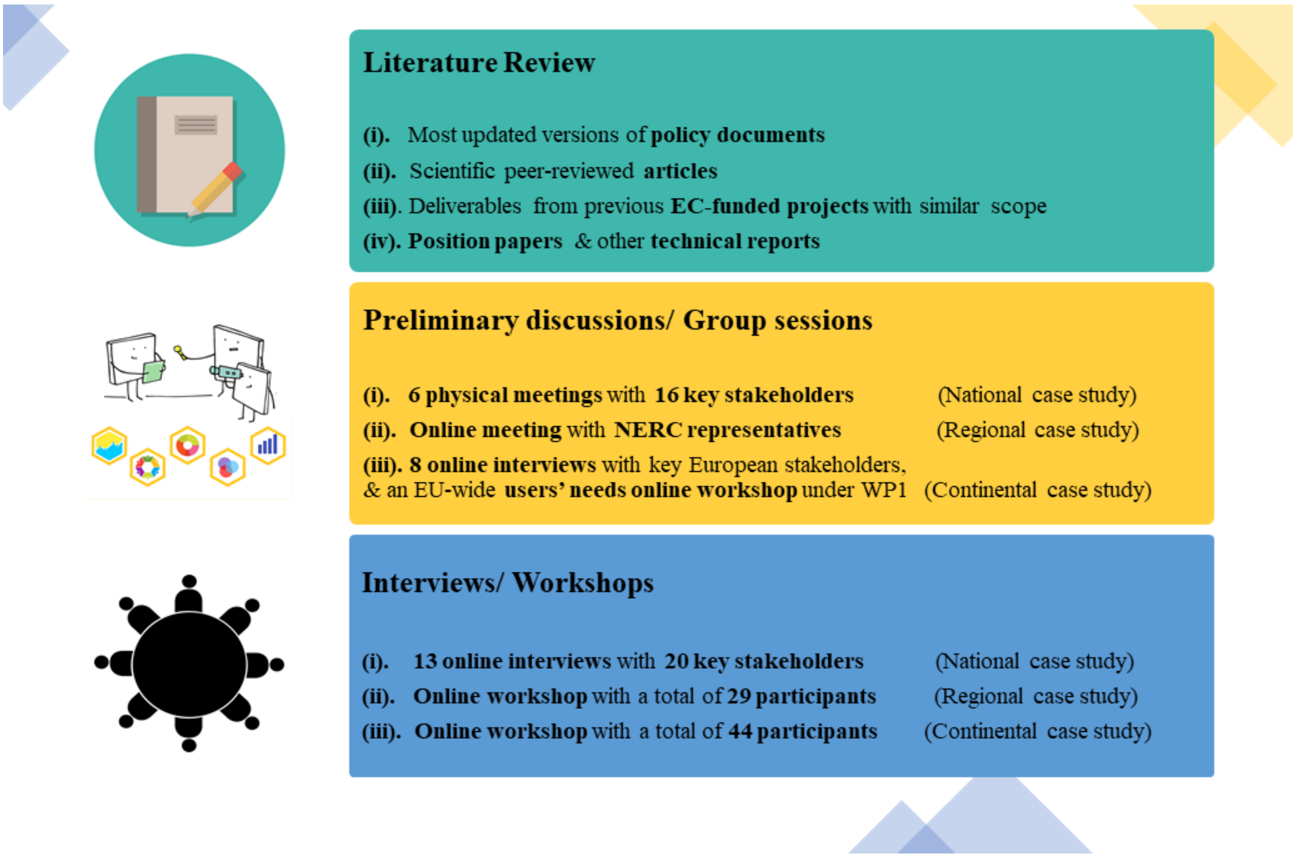
relevant contextual questions, which energy system models should be able to respond to, also considering new modelling trends and paradigms, as identified under WP1 (Gaschnig et al., 2020). Here, we present our findings which include a large number of various research questions, which could serve as a comprehensive reference list for stakeholders, interested in an updated overview on the latest policy developments, the critical issues and challenges of the energy transition in diverge spatial scales, or in the socioeconomic contexts under study.

1.3. Structure of this report

The remainder of this Deliverable is structured as follows: **Section 2** presents our participatory multi-methods approach to develop robust specifications and identify the key critical issues, knowledge gaps, challenges, and research questions that the SENTINEL models will attempt to provide answers to, for each one of the case studies. **Section 3** presents the case study scenarios and the main underlying narratives, definition of the main scenarios' parameters, and collection of the important research questions. Finally, **Section 4** discusses the main findings of our work and provides a comparative overview between the case studies in order to highlight the common issues in the energy transition irrespectively of the size, geographic extend, and complexity of the energy system. It also highlights the main limitations of our work and presents in short the next steps towards model application of different energy transition pathways for the SENTINEL case studies.

2. A participatory multi-methods approach

To identify and specify the policy relevant scenarios, the critical issues and challenges, and the research questions of the energy transition towards 2050, which SENTINEL models will need to provide answers to, for all the three case studies, we have applied a three-tier participatory multi-methods approach, as presented in **Figure 2**.



Literature Review

(i). Most updated versions of **policy documents**
(ii). Scientific peer-reviewed **articles**
(iii). Deliverables from previous **EC-funded projects** with similar scope
(iv). **Position papers** & other **technical reports**

Preliminary discussions/ Group sessions

(i). **6 physical meetings** with **16 key stakeholders** (National case study)
(ii). **Online meeting** with **NERC representatives** (Regional case study)
(iii). **8 online interviews** with key European stakeholders, & an EU-wide **users' needs online workshop** under WP1 (Continental case study)

Interviews/ Workshops

(i). **13 online interviews** with **20 key stakeholders** (National case study)
(ii). **Online workshop** with a total of **29 participants** (Regional case study)
(iii). **Online workshop** with a total of **44 participants** (Continental case study)

Figure 2. A three-tier participatory multi-methods approach as applied to all the three SENTINEL case studies.

Tier 1

The first tier of our approach included a literature review to specify the main energy transition scenarios to which the SENTINEL models will run, along with preliminary contextual critical issues/ challenges and research questions.

Regarding policy documents we reviewed the most updated ones, as National Determined Contributions (NDCs) under the Paris Agreement, National Energy and Climate Plans (NECPs), and Energy Roadmaps towards 2050. For the Regional and the Continental case studies, we reviewed policy documents to specify scenarios and targets at an aggregated level, along with individual national commitments.

Regarding scientific literature, our review was based on a broad search in energy-related peer-review journal articles found in the scientific databases 'Science Direct' and 'Google Scholar'. For our search we used indicative keywords, as "Energy transition", "Energy scenarios", "Climate and energy targets", "Decarbonisation", "Climate neutrality" AND "Greece", "Nordic region", "Denmark", "Finland", "Norway", "Sweden", "Iceland", "Europe", "Switzerland" and "United Kingdom". Search results were limited to the period 2015- 2020.

For the case of grey literature, the search process was focused on the inclusion of relevant technical reports and positions papers to build on existing knowledge and experience. Search results were also limited to the period of 2010- 2020 for this case too. Finally, we also made use of knowledge from deliverables from EC-funded projects with similar scope, like the Horizon 2020 "openENTRANCE" project[5] (the 'sister project' of SENTINEL), and insights from the Energy Modelling Platform for Europe (EMP-E) 2020 online conference[6].

Findings from the first Tier were used to guide our work on the next two Tiers, which were structured around stakeholder engagement activities. Stakeholders were involved at different stages of the case study specification process. We engaged diverse stakeholders (considered also as "storytellers") with differentiated views on the critical issues of the energy transition to combine multiple perspectives and sources of expertise about possible future developments of the Greek, Nordic, and European energy systems. This approach helped us to reduce uncertainties underlying in the different possible future developments, and to result at a potential "development corridor".

Tier 2

At the second Tier of our approach, we met key representatives from each case study to validate and enrich our preliminary findings on the climate and energy scenarios specified, and on the contextual critical issues/ challenges and research priorities identified.

For the National case study, we conducted 6 physical meetings with 16 stakeholders from policymaking, industry, and academia/ science, to reflect on the national scenarios and targets suggested in the recent National Energy and Climate Plan, and the Long-Term Strategy 2050. This discussion included also specific scenario assumptions, which should be considered by further modelling exercises. In these meetings participated: representatives from the Greek Ministry of Environment and Energy (MEE), the Centre for Renewable Energy Sources (CRES), the Energy-Economy-Environment Modelling Laboratory (E^{3}MLab) from the National Technical University of Athens (NTUA), and from different departments of the Public Power Corporation S.A. (PPC) and the Independent Power Transmission Operator S.A. (IPTO). All these entities played a key role in the development of the two policy documents above.

After specifying the energy scenarios and targets and reflecting on preliminary critical issues/ challenges and research priorities for the Regional case study, we organised an online meeting with representatives from the Nordic Energy Research Council (NERC)- the cooperation platform for energy research and policy development under the auspices of the Nordic Council of Ministers[7]. Our discussion focused mainly on the specifications of the existing "Carbon Neutral Scenario" for the region, and specific thematic priorities, which would be of interest to their work. This meeting established a direct communication channel with NERC, which we intend to exploit by using the SENTINEL modelling suite to simulate the upcoming

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[5] https://openentrance.eu/
[6] http://www.energymodellingplatform.eu/emp-e-2020.html
[7] https://www.nordicenergy.org/

updated climate neutrality scenarios for the region, provide answers to critical issues of the energy transition in the Nordic countries as well as to support NERC towards robust decision-making.

Finally, for the Continental case study, we considered recent available policy documents (e.g., National Determined Contributions, Green Deal communication documents, the Renovation Wave, the Circular Economy Action Plan, the New Industrial Strategy for Europe, etc.), and political processes (e.g., update of the emissions reduction target by 2030, or the discussion about the new EU Multiannual Budget 2021-2027, including the Recovery Package, etc.) to specify the energy transition scenarios and targets, and the thematic priorities. During this stage of our approach, we made use of the synergies developed since the start of the project within WP1. In particular, 8 interviews with key European stakeholders, the EU-wide survey and an online workshop enabled us to understand modelling users' needs towards EU climate neutrality by 2050. These activities gave us the chance to discuss about specifications of energy transition scenarios in Europe, and contextual research priorities, enriching our preliminary work under Tier 1.

After these two first Tiers, energy transition scenarios and targets have been specified for all the three case studies. The identified along with thematic sections suggested the key research priority areas for each case. In addition, we identified a preliminary set of contextual critical issues/ challenges and research questions, and categorised them under the individual themes, according to their conceptual characteristics and relevance, and stakeholders' initial feedback.

Tier 3

Finally, during the third Tier of our approach, we conducted interview meetings and thematic workshops with a larger sample of stakeholders.

Coronavirus-specific related issues and corrective actions

According to the initial planning of this stage of our approach, we aimed at organising three thematic, one-day, physical workshops with key stakeholders and representatives from each case study. The National case study workshop was supposed to take place in April 2020, the Regional case study workshop in June 2020, and the Continental case study workshop in September 2020.

For the National event, we made most of arrangements: we reserved a venue for the 7th of April 2020 and invited relevant stakeholders, with more than 20 invitees having registered for the event. A detailed agenda of this meeting is presented in **Section A1.** Agenda of the National level case study workshop that was cancelled in **Appendix**. However, given the spread of the COVID-19 from late February 2020, we decided to cancel the physical event and host it as a webinar. However, representatives from the Ministry of Environment and Energy advised us to wait even with an online meeting, due to the uncertainty of the situation at the time and the complete lockdown in Greece starting mid-March 2020.

This called for a complete restructuring of our initial approach regarding the thematic events under all three case studies. To this end, we used the period March-May 2020 to adapt to the new reality, investing additional resources to the design of specific online formats, which would allow us to organise interactive stakeholder engagement activities.

Since the National case study was supposed to serve as the pilot for the next ones, we shared with the stakeholders expected to participate in the physical event, a narrative document that we have produced so far. It synthesised all findings from Tier 1 and Tier 2 and by collecting stakeholders' initial feedback, we aimed at adding an extra layer of validation. In the meantime, we also started organising bilateral online interviews with the same stakeholders. These meetings started just by early June, because until then reaching out to them was difficult: many of them were either irresponsive or needed additional time to adapt to new circumstances of the COVID-19 situation.

In the meantime, we shared our work with the SENTINEL modellers to receive their feedback on the simulation feasibility of the case study scenarios, on variables and assumptions necessary to calibrate/ parameterise their models, and on the contextual critical issues/ challenges and research questions to be replied by their models. Finally, during the same period, we started the preparations to host online workshops for the two remaining case studies, i.e., the Regional and the Continental, during November and December 2020.

In result, between June-December 2020, we conducted for the National case study, 13 online interview meetings with 20 key stakeholders, during which we validated our thematic research priorities and specified more than 80 research questions for the SENTINEL modelling suite. The interview meetings were based on a semi-structured design as well as an open discussion format, to allow stakeholders to freely express their opinions.

For the Regional case study, we conducted an online workshop on the 4th of November (a detailed agenda of the workshop can be found in **Section B1.** Agenda of the Regional level case study workshop in **Appendix**) with a total of 15 stakeholders from all the Nordic countries, which represented energy industry, the policymaking sphere, NGOs, and academia. Representatives from the NERC also participated in the event. Similarly, for the Continental case study, we conducted an online workshop on the 9th of December (a detailed agenda of the workshop can be found in **Section C1.** Agenda of the Continental level case study workshop in **Appendix**) with a total of 26 stakeholders from different European countries. Similarly, as in the Nordic case study workshop, participants represented energy industry, the policymaking sphere, NGOs, and academia, including one representative from the European Commission's Joint Research Centre (JRC).

Each online workshop consisted of an opening plenary session with an introduction presenting the objectives of the events, embedded in the broader SENTINEL framework. These were followed by two parallel break-out sessions and a closing plenary session. Each of the parallel breakout sessions consisted of different breakout rooms based on the thematic areas identified during Tier 2, which focused on different research priorities of the Nordic and the European energy systems. Each of the thematic sessions was facilitated by SENTINEL modellers, whose model(s) is(are) able to deal with the various issues related to the scope of the selected thematic areas. After the first break-out session, we rotated the stakeholders into different breakout rooms to guarantee an exchange among people with different backgrounds. Both thematic events allowed us to completely specify the energy transition scenarios and respective targets, also reflecting on key assumptions/ parameters that should be taken into account during modelling simulations. Thanks to these events we validated our thematic research priority areas and specified more than 150 research questions for the SENTINEL modelling suite, for both the Regional and the Continental case studies.

As in the reformulated process followed for the National case study, we added an extra layer of validation, by sharing our work again with SENTINEL modellers, before and after the two workshops. That allowed us to receive their feedback on the simulation feasibility of the case study scenarios, on variables and assumptions necessary to calibrate/ parameterise their models, and on the contextual critical issues/ challenges and research questions. Finally, some research questions for all the case studies were directly formulated based on the content of the SENTINEL models, namely their scope, key assumptions, inputs, and outputs. To accomplish this task, we utilised the models' documentation templates prepared by each modelling team within the SENTINEL project.

As theoretical underpinning of our work, we applied the "**Three types of knowledge**" tool, which "*serves in reformulating research questions in order to check what (societal) knowledge demands the questions meet*" (Network for Transdisciplinarity Research, 2021). The generated questions stress different types of required knowledge, namely: **(i).** "*knowledge about what is*" ("**Systems knowledge**"), **(ii).** "*knowledge about what should be*" ("**Target knowledge**"), and **(iii).** "*knowledge about how we come from the point where we are, to the point where we should be*" ("**Transformation knowledge**"). The first of the guiding questions presents the actual state of specific areas in the energy system, whereas the two following questions concern the energy targets and the future transformation pathways. Within all stakeholder consultation activities, we addressed all three types of knowledge in each case study thematic area, as presented in **Table 1**. Application of this tool allowed us to guarantee a systematic process of identification of the specific case study features, such as critical issues/ challenges and contextual research questions.

Table 1. Analytical underpinning of the case study identification approach.

Type of knowledge	***System knowledge***	***Target knowledge***	***Transformation knowledge***
Guiding question	"***Where we are?***" (in the context of the energy transition)	"***Where we want to get to?***" (with regards to targets per sector towards energy transition)	"***How do we get there?***" (in terms of the policy tools that will be required to get to the targets)
Data collection & operationalisation	Measurable and timely progress (statistical data)	Measurable and timely progress (statistical data) & Stakeholder preferences	Technical solutions & Mix of initiatives & Stakeholder preferences

For the "**Transformation knowledge**", it was essential to consider key drivers/ challenges and features of possible future developments for each one of the case studies. We perceived future developments, not only in terms of technological innovations and deployments, but also in terms of social acceptance, political feasibility, and role of decision-makers, among others. In that context, narratives or storylines can provide a broader picture of potential future developments (pathways) and can also encapsulate a number of "softer" aspects that cannot be modelled yet. Different storylines or narratives might be dominated by different interacting governance logics as well as different technological and institutional changes are caused, and different engineering and social challenges may arise (Foxon, 2013; Foxon, Hammond, & Pearson, 2010). As a final step, thus, we analysed and used the insights from consultation events to update the narratives of each case study.

Table 2 summarises our progress so far under the SENTINEL WP7 Key Performance Indicators (KPIs) and metrics for the different activities conducted to specify the energy transition scenarios and targets, along with the contextual critical issues/ challenges and specific research questions for each one of the case studies under the SENTINEL Task 7.1.

Table 2. Progress summary: An overview of the Key Performance Indicators (KPIs) and metrics for all the different activities conducted for each SENTINEL case study during the period October 2019- February 2021.

SENTINEL ***Case study***	***Literature review*** **(Tier 1)**	***Preliminary discussions/ Group sessions*** **(Tier 2)**	***Online Interviews*** **(Tier 3)**	***Online Workshop***
National ***(Greece)***	Yes (**50** literature sources)	**6** physical meetings with **16** key stakeholders	**13** online interviews with **20** key stakeholders: policymakers, energy industry, NGOs & academia/ research	-
Regional ***(Nordic countries)***	Yes (**27** literature sources)	**1** online meeting with NERC representatives	-	Online workshop with a total of **29** participants: policymakers, energy industry, NGOs, academia/ research, and SENTINEL modellers
Continental ***(EU, Iceland, Norway, Switzerland, & UK)***	Yes (**53** literature sources)	**1** online workshop, **8** interviews **1** EU-wide survey (all under WP1)	-	Online workshop with a total of **44** participants: policymakers, energy industry, NGOs, academia/ research, and SENTINEL modellers

Overall, despite the difficult circumstances related to the COVID-19 pandemic, we reached out to more than 250 stakeholders, from the different SENTINEL target groups, while we engaged with more than 80 key stakeholders in the context of the three case studies (**Figure 3**).

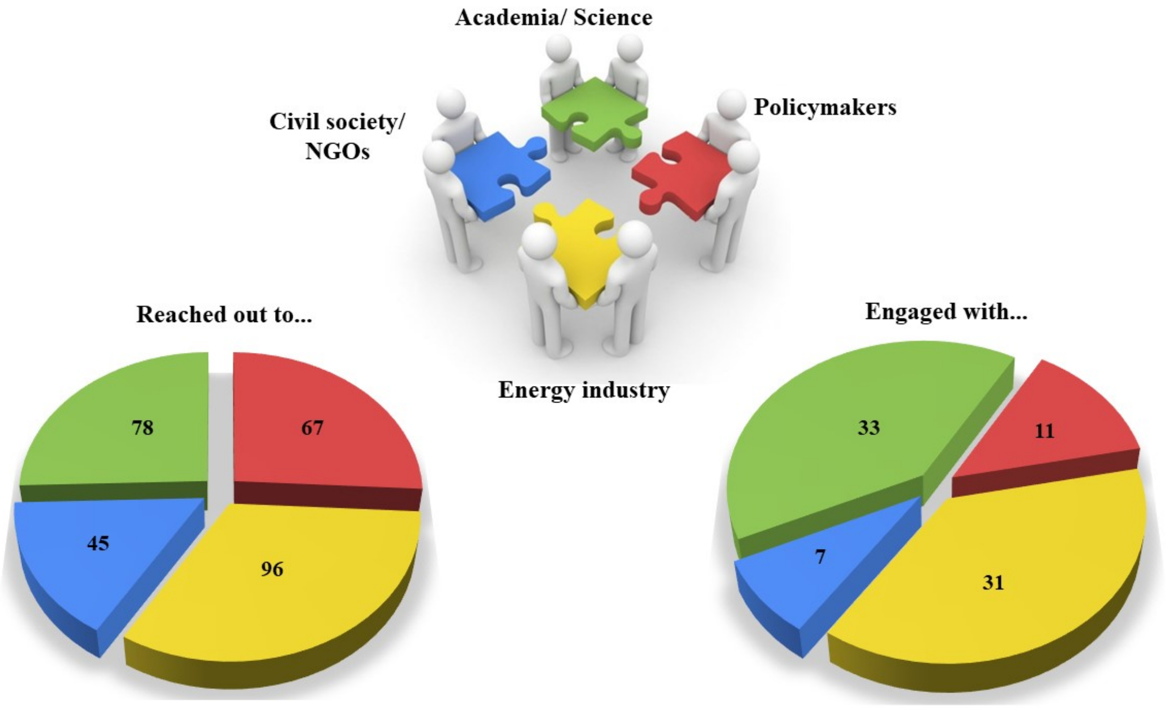


Figure 3. Overall stakeholder engagement activities under WP7 during the period October 2019- December 2020, for all the three SENTINEL case studies.

3. Case specifications & scheduling

By applying the approach presented in **Section 2**, we developed case study narratives, which consist of the following elements: most updated policy-relevant scenarios and targets to be simulated, along with contextual critical issues and technical/ institutional transformation challenges for reaching the energy targets, and specific research questions that the SENTINEL modelling suite will attempt to provide answers to.

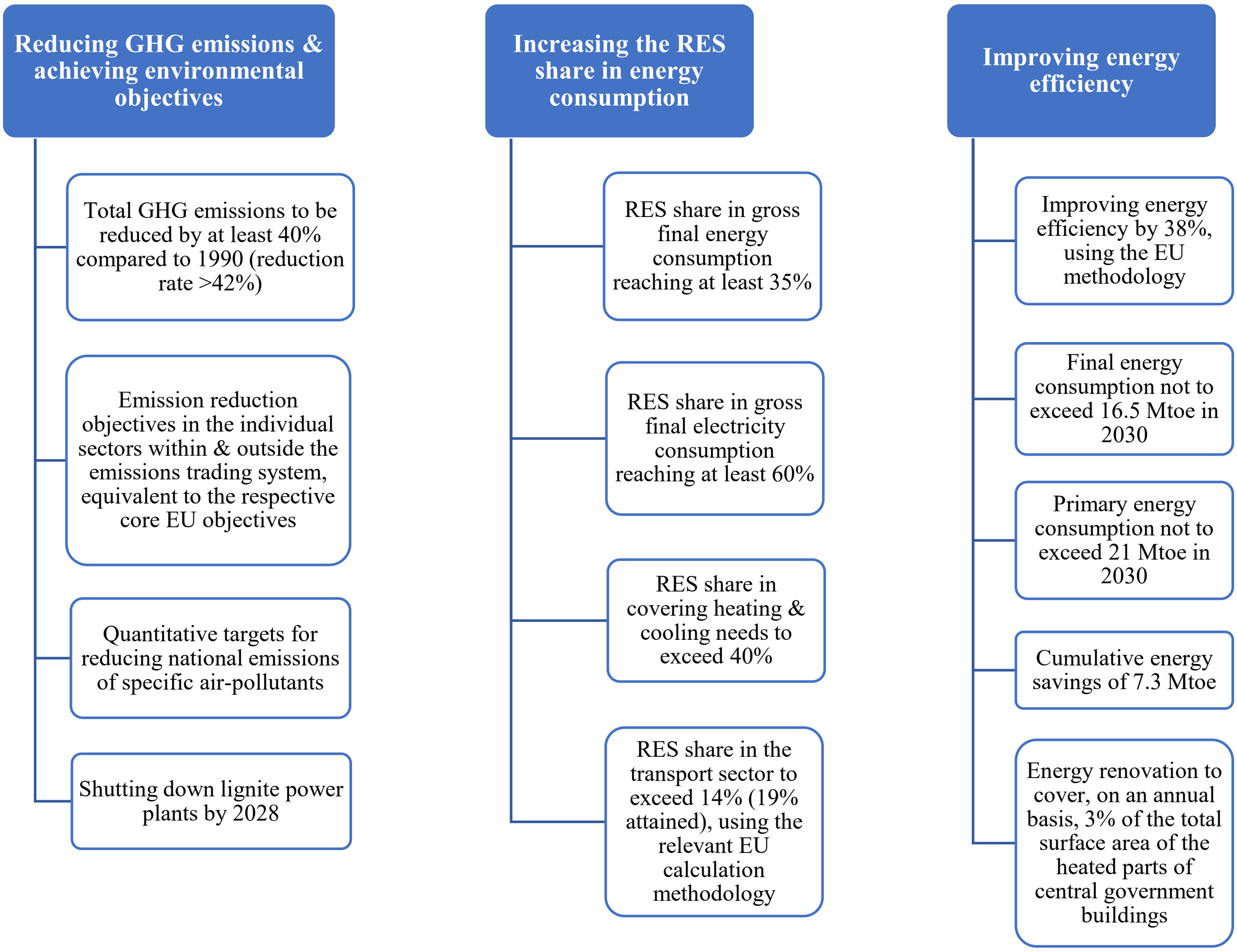
3.1. National level case study: "Energy transition in Greece towards 2030 & 2050: Critical issues, challenges & research priorities"

Greece is a transcontinental country with a diverse geographical landscape and a large potential in renewable energy (Vassilis Stavrakas & Flamos, 2020). It presents a very recent case of a radical change in the planning of the energy system development. Although the introduction of renewable energy was actively promoted in the energy policy agenda over the past ten years (Nikas et al., 2019), indigenous lignite continued to play a major role in the electricity generation in all scenario analysis and policies formulated until 2019. However, in the second half of 2019, Greece took the political decision of phasing-out lignite-fired power plants in a short time horizon (by 2028), which calls for extensive modelling work to analyse its effect on the further development of the national energy system.

3.1.1. Background on Policies & Targets

While the policy targets for the energy sector by 2030 in Greece are well-defined and expressed in the National Energy and Climate Plan (NECP), the pathway to 2050 is still being investigated and various options are analysed in alternative scenarios. According to the recently published version of the Greek NECP (Ministry of Environment and Energy, 2019b), Greece has committed to the redesign of the energy sector from production to end-use, along the axes of *sustainability*, *environmental protection*, and *climate change mitigation*. Special focus is also given to *energy security* and *affordability for all*. Towards this direction, the diversification of *energy supply* and the *energy independence* of the country are of primary importance, enhancing the role of Greece as *energy hub*, promoting *financial stability*, and facilitating *resource management*. Furthermore, the design of **competitive energy markets** is crucial to promoting sustainability and transparency in product and service provision as well as their price. Finally, as new competitive technologies enter the market, innovation in terms of investments and activities is promoted. The national targets for 2030 set in the context of the NECP are presented in **Figure 4**.

For the achievement of these targets the NECP lays down policy priorities, which are defined along the dimensions of the Energy Union, which aim at: **(i) decarbonisation in terms of both GHG emissions and removals and renewable energy**, improving **(ii) energy efficiency (EE)** and **(iii) energy security**, and **enhancing (iv) the internal energy market** and **(v) research, innovation, and competitiveness**. Particular areas of interest for additional sectors as **agriculture**, **shipping**, and **tourism** are also included.



- **Reducing GHG emissions & achieving environmental objectives**
  - Total GHG emissions to be reduced by at least 40% compared to 1990 (reduction rate >42%)
  - Emission reduction objectives in the individual sectors within & outside the emissions trading system, equivalent to the respective core EU objectives
  - Quantitative targets for reducing national emissions of specific air-pollutants
  - Shutting down lignite power plants by 2028
- **Increasing the RES share in energy consumption**
  - RES share in gross final energy consumption reaching at least 35%
  - RES share in gross final electricity consumption reaching at least 60%
  - RES share in covering heating & cooling needs to exceed 40%
  - RES share in the transport sector to exceed 14% (19% attained), using the relevant EU calculation methodology
- **Improving energy efficiency**
  - Improving energy efficiency by 38%, using the EU methodology
  - Final energy consumption not to exceed 16.5 Mtoe in 2030
  - Primary energy consumption not to exceed 21 Mtoe in 2030
  - Cumulative energy savings of 7.3 Mtoe
  - Energy renovation to cover, on an annual basis, 3% of the total surface area of the heated parts of central government buildings

Figure 4. National targets of the energy transition in Greece by 2030 for the three main priorities outlined in the Greek Energy and National Plan. Source: (Ministry of Environment and Energy, 2019b). Adapted by the authors.

3.1.2. Energy Scenarios & Narratives

Energy scenarios towards 2030 and 2050 in the Greek case study consider the evolution of all sectors and aim at evaluating the challenges for the achievement of the national energy and climate targets, as well as their implications.

3.1.2.1. "Reference" (RF) Scenario (2020- 2050)

Following the NECP, the main objectives for the Greek energy system in 2030 are:

- **GHG emissions** should be reduced by almost **43%** compared to emissions in **1990**, and by **56%** compared to emissions in **2005**. Total GHG emissions should be around **60.6 MtCO$_2$eq**.
- **RES** should contribute with a minimum share of **35%** to *gross final energy consumption*. RES share in *gross final electricity consumption* should exceed **60%**, fluctuating around **61-64%**. *Lignite generation* holds **0%** share in electricity production.
- The *final energy consumption* in **2030** should be around **16.1-16.5 Mtoe**. An objective of **at least 38%** of EE improvement with relevance to the *foreseen final energy consumption* in **2030** and

achieving lower *final energy consumption* in **2030** compared to that in **2017**, has been set to attain *cumulative energy savings* of **7.3 Mtoe** during the period 2021-2030.

The electricity system is decarbonised through the promotion of RES and by limiting the operation of carbon intensive generating resources. RES will be the dominant source of power generation, exceeding 65% of the domestic power generation and amounting to 61.6% of the total electricity generation in 2030 (Ministry of Environment and Energy, 2019a). The total RES capacity for power generation in 2030 will be equal to 19 GW, with hydro plants consisting of 3.9 GW, while power generation from wind and PV plants will increase from 17% in 2017 to 45%, with installed capacity of 14.7 GW, i.e., 7 GW in wind and 7.7 GW in PV. Additional new auto-production and net-metering PV systems of 600MW are to be installed until 2030 with an aim to overcome 1 GW of installed capacity. The RES capacity in 2050 is expected to be equal to 26.5 GW. Wind and PV capacities in 2050 are expected to be 10.2 GW (including 0.4 GW of offshore wind) and 11.2 GW, respectively, and hydro capacities remain at the same capacity levels, i.e., 4.0 GW. Regarding electricity generation in 2050, RES penetration is expected to be around 84% of the total electricity generation.

The total energy utilisation of storage (i.e., pumped hydro, battery energy storage systems (BESS), and hydrogen) is estimated at 2.2 TWh in 2030, with installed power capacities equal to almost 1.6 GW for pumped hydro, 1.2 GW of BESS and small shares of hydrogen, while in 2050, the expected energy utilization by storage systems is equal to 8.2 TWh, with installed power capacities equal to 1.7 GW of pumped hydro, 2.6 GW of BESS and 0.4GW of hydrogen. RES aggregators (i.e., legal entities which cumulatively represent RES generators in the electricity markets) are starting to operate, however, most of the systems supply their energy through the currently established tendering processes, which will continue until 2050. At the same time, all lignite-fired power plants will be phased out by 2023, except for the 'Ptolemaida 5' plant, whose commissioning started in 2020 and will be retrofitted to generate electricity from natural gas from 2028 onwards (eleftheriaonline.gr, 2019; insider.gr, 2019). As a result, the share of lignite in power generation will be equal to zero in 2030 and 2050. Natural gas serves as an intermediate fuel, with a capacity of 6.91 GW in 2030. In 2050, thermal units' capacity is expected to be 6.5 GW. Interconnection reinforcement with neighbouring countries is also promoted, as a means of increasing electricity capacity to meet demand, and for cost containment in peak demand periods.

The expected electricity supply in 2030 is equal to 61.8 TWh, while in 2050, the expected electricity supply equals 80.3 TWh. RES is expected to contribute to the gross final energy consumption in 2030 with a share of 67.6%. Primary energy consumption will be ca. 20.5 Mtoe in 2030 and will drop to 16.1 Mtoe in 2050. Energy intensity is expected to be reduced by 32% between 2020 and 2030, and further reduced around 30% (total 62%) until 2050. The RES share in the gross final consumption for heating and cooling is expected to reach 42.5% (bioenergy 46.4%, solar 16.8%, and geothermal 36.8%) in 2030, and around 52% in 2050. The RES share in gross final consumption for transport is projected to be 19% (biofuels 79.8% and electricity from RES 20.2%) in 2030, and around 230% in 2050 (number high due to the EU calculation formula). The total number of residential buildings to be renovated until 2030 is 600.000, while in 2050 the total number of renovated residential buildings is expected to reach 856.000. The final energy consumption in the residential sector is expected to be covered by electricity (39.1%), bioenergy (19.3%), and natural gas (15.1%), followed by petroleum products (9.7%), solar energy (8.4%), RES in the form of heat pumps (7.5%), and district heating (0.9%) in 2030. In 2050, electricity use in households is expected to rise to 58.9%, whereas natural gas will account for 21.7%, bioenergy for 9.9%, RES for 8.6%, district heating for 0.7%, and petroleum products and fossil fuels only for 0.2% of the final energy consumption.

Electrification in transport is promoted through the full electrification of track-based modes until 2030 and through the gradual promotion of passenger electric cars (Battery Electric Vehicles and Plug-in Hybrid Electric Vehicles), whose total number is expected to increase by 278,254 vehicles until 2030, reaching a total number of 6,029,000 vehicles by 2050. In 2030, the energy consumption of the transport sector accounts for 91.1% from petroleum products, 5.3% from bioenergy, 1.4% from natural gas, and 2.2% from electricity. Full electrification will have been achieved in rail transport by 2030. In 2050, still, fossil fuels have the dominant, yet reduced, role regarding final energy consumption of the transport sector, equal to 63.2% (liquid fossil fuels and bunker fuels). Natural gas and biogas account for 6.1%, bioliquids for 20.5%, electricity for 8.7% and hydrogen for 1.5% of the sector's final energy consumption. In the industrial sector, electricity will become the dominant source of energy with a share of 39.6%, followed by natural gas (26.7%), petroleum products (20.4%), bioenergy (7.9%), and solid fuels (5.2%) in 2030. The industrial sector is expected to be electrified by 53.5% in 2050, with natural gas, biogas, biofuels, and RES covering the remaining share.

Finally, emission reduction targets of certain air pollutants for 2030 are provided in **Table 3**. Overall, GHG emissions are expected to be mitigated by 74.7% until 2050 with relevance to 1990 levels. Total GHG emissions will amount to 27.2 $MtCO_2eq$. Note that these target projections for 2030 are considered the same also for the next two scenarios.

Table 3. Emissions reduction targets of certain air pollutants for 2030 compared to 2005 levels (Ministry of Environment and Energy, 2019b).

Air pollutants	% of emission reductions
Carbon dioxide (CO_2)	88%
Sulphur dioxide (SO_2)	88%
Nitrogen oxides (NO_X)	55%
Non-methane volatile organic compounds (NMVOCs)	62%
Ammonia (NH_3)	10%
Fine particulate matter (PM2.5)	50%

3.1.2.2. "Renewable Electricity" (RE) Scenario (2030- 2050)

In this scenario, the pathway described in the RF scenario from 2020 to 2030 is followed, while in the pathway from 2030 to 2050, emphasis is given on the decarbonisation of the electricity system through the installation of variable RES. The penetration of RES in total electricity generation is expected to be around 97.3% in 2050. The total RES capacity in 2050 is equal to 33.9 GW. Wind and PV capacities are projected to rise to 13.4 (0.6 GW of which offshore) and 14.6 GW, respectively in 2050, while hydropower reaches 4.7 GW. Furthermore, the lignite share in the electricity mix is zero, and natural gas units which operate mostly with synthetic gas, serve as system stabilisers with a total capacity projected equal to 4.9 GW in 2050. Interconnections with the neighbouring countries are strengthened more than in the RF scenario to manage situations of extreme RES intermittency. In 2050, the expected electricity supply will be 100.9 TWh.

RES generators supply electricity either under a Feed-in Premium (FiP) contract awarded through a tendering process, or by participating in the wholesale electricity market, or by signing a direct contract with consumers. In all situations, aggregators serve as representation entities for RES generation/ integration. The expected energy utilisation by storage systems is equal to 22.4 TWh, with installed power capacities equal to 1.7 GW for pumped hydro, 2.5 GW for BESS and 4.3 GW of hydrogen (Ministry of Environment and Energy, 2019a). Multiple BESS are grouped into virtual power plants and provide the missing power in cases where RES generation is low and demand is high (service to aggregators), or when voltage deviations occur (service to Transmission System Operators (TSOs)), and the total electricity transmitted to BESS is 5.9 TWh in 2050. Digitalisation of energy management is a significant component of such an energy system. Demand-side flexibility, smart microgrids, and energy blockchains are developed allowing the maximum utilisation of RES generated electricity.

On the demand side, improving EE is a key priority. Energy intensity is expected to be reduced by 32% between 2020 and 2030, and further reduced around 30% (total 62%) until 2050. RES will have a 95.9% share in the gross final energy consumption in 2050. Total primary energy consumption is expected to drop to around 15.2 Mtoe. The RES share in gross final consumption for heating and cooling is expected to reach around 81% in 2050. The RES share in gross final consumption for transport is projected to be around 494.7% in 2050. In the residential sector, the final energy consumption is expected to be 45-57% lower compared to the 2005 levels. In 2050, renovated residential buildings will reach the 1,136,000 in total, while electricity use in households will rise up to 81%, with RES accounting for 10.2%, bioenergy for 7.9%, natural gas for 3%, and district heating and petroleum products and fossil fuels for small shares of the final energy consumption. Smart-meters are installed in all premises until 2030, enabling day-ahead and real-time demand-response activities.

Electrification in passenger transport reaches the total number of 8,011,000 electric vehicles in 2050. In 2050, fossil fuels have a significantly reduced role regarding final energy consumption of the transport sector, equal to 39.6% (liquid fossil fuels and bunker fuels). Natural gas and biogas account for 1.3%, bioliquids for 40.4%, electricity for 17%, and hydrogen for 1.7% of the transport sector's final energy consumption. Digitalisation in the transport sector reveals new business models in which car batteries serve as an energy resource when the vehicle is stationary, providing services to the grid. Finally, the industrial sector is electrified by 63% in 2050, with natural gas, biogas and biofuels covering the remaining 37%.

Overall, GHG emissions are reduced by 94.7% until 2050 with relevance to 1990 levels. Total GHG emissions are expected to be equal to 5.7 $MtCO_2eq$.

3.1.2.3. "Power-to-X" Scenario (P2X) (2030- 2050)

In this scenario, the pathway described in the RF scenario from 2020 to 2030 is followed again. RES technologies reach the same level as in the RE scenario, however, not all RES generated electricity is directly consumed. Regarding the pathway from 2030 to 2050, part of the RES generated electricity is used to produce hydrogen and e-fuels or synthetic fuels, as intermediate energy storage commodities, which could further be used for electricity generation through combustion or hydrogen fuel cells. Similar to the RE scenario, RES penetration is expected to reach around 97.3% of total electricity generation in 2050 and RES generators are represented by aggregators. The total RES capacity in 2050 is projected to be 63.8 GW. Wind and PV capacities are projected to rise to 19.7 GW (2.2 GW of which offshore) and 37.3 GW, respectively, with hydro plant capacities being at 5.1 GW. In 2050, existing natural gas-fired units of 7.9 GW are fuelled by synthetic gas and the expected electricity supply will be 173.2 TWh.

Energy storage is projected to evolve beyond system stabilisation, with expected energy utilisation of 42.4 TWh and installed power capacities equal to 1.5 GW for pumped hydro, 3 GW for BESS, and 23.5 GW of hydrogen. Direct and indirect hydrogen storage of (33.1 TWh energy utilisation) is expected to become a mature technology, and excess RES electricity is not curtailed, but it is used to produce hydrogen and is stored. Also, the total electricity transmitted to BESS is 8.8 TWh in 2050. In this scenario, virtual power plants exist for electricity system stabilization and e-fuel supplies are managed by virtual energy plants.

Digitalisation plays an important role. Smart electricity grids are upgraded into smart energy grids, making use of cloud services, demand-side flexibility, and blockchain technologies to manage all renewable energy (i.e., electricity and e-fuels).

On the demand side, primary energy consumption is expected to rise to 24 Mtoe by 2050 and RES share in gross final energy consumption will reach 113.8%. Similar reduction in energy intensity is expected between 2020 and 2030 with regards to the other scenarios, however, energy intensity will be reduced only by 8% until 2050. In 2050, renovated residential buildings will reach 956.000. RES cover 92.9% of the heating and cooling needs and around 330% of the transport needs in 2050. In the residential sector, the final energy consumption is expected to be 45-57% lower compared to the 2005 levels. In 2050, natural gas is not used. Electricity use in households rises to 59.2%, synthetic methane accounts for 15.7%, bioenergy accounts for 11.9%, RES for 7.9%, hydrogen for 4.5%, while district heating, petroleum products and fossil fuels contribute with small shares to the final energy consumption.

Fuel-cells usage in passenger transport is expected to start after 2030 and could potentially reach around 3% until 2050. The rest of the passenger transport vehicles will be mostly electric (around 91%), hybrid and conventional (around 6%). Electric passenger cars will amount to 7,607,000 vehicles. Fuel cells' usage in buses and tracks could potentially reach around 14% until 2050. The rest of the buses and trucks will be electric (around 4%), hybrid and conventional (around 82%). Fossil fuels have a significantly reduced role regarding final energy consumption in the transport sector, equal to 37.9% (liquid fossil fuels and bunker fuels) in 2050. Synthetic liquid fuels and synthetic methane account for 26.5%, natural gas and biogas account for 2%, bioliquids for 15%, electricity for 12%, and hydrogen for 6.6% in the sector's final energy consumption. Finally, regarding industrial processes, biofuels, biogas, hydrogen, and synthetic fuels are the main complementary energy sources to electricity (55%), reaching around 40% until 2050.

Overall, GHG emissions are reduced by 95.3% compared to 1990 levels until 2050. Total GHG emissions will be 5 $MtCO_2eq$.

All the main specifications of the energy transition scenarios for the SENTINEL National case study, along with the respective targets, are presented in detail in **Table 4**.

Table 4. Summary of the energy scenarios and targets for the National case study in Greece.

Scenario	**RF (2020- 2030)** **Values for 2030**	**RF (2030- 2050)** **Values for 2050**	**RE (2030- 2050)** **Values for 2050**	**P2X (2030- 2050)** **Values for 2050**
Total GHG reduction targets	-43% relative to 1990 (-56% relative to 2005)	-74.7% relative to 1990	-94.7% relative to 1990	-95.3% relative to 1990
Total GHG emissions (Mt CO_{2eq})	60.6	27.2	5.7	5.0
RES & efficiency targets	**1.** >35% RES in gross final energy consumption **2.** 61.6% RES in total electricity generation, 0% lignite in electricity generation	**1.** 67.6% RES in gross final energy consumption **2.** ~52% RES in gross final energy consumption for heating and cooling	**1.** 95.9% RES in gross final energy consumption **2.** ~81% RES in gross final energy consumption for heating and cooling	**1.** 113.8% RES in gross final energy consumption **2.** ~92.9% RES in gross final energy consumption for heating and cooling

	3. >38% EE improvement (compared to the forecast on final energy consumption by 2030 and to achieve lower final energy consumption in 2030 compared to that in 2017), leading to energy savings of 7.3 Mtoe (2021– 2030)	**3.** ~230%* RES in gross final energy consumption for transport,	**3.** 494.7%* RES in gross final energy consumption for transport	**3.** ~330%* RES in gross final energy consumption for transport
	4. final energy consumption: 16.1–16.5 Mtoe, primary energy consumption: 20.5 Mtoe	**4.** ~84% RES in total electricity generation, primary energy consumption: 16.1 Mtoe	**4.** ~97.3% RES in total electricity generation, primary energy consumption: 15.2 Mtoe	**4.** ~97.3% RES in total electricity generation, primary energy consumption: 24 Mtoe
	5. -32% energy intensity (2020 – 2030)	**5.** -30% energy intensity (2030- 2050)	**5.** -30% energy intensity (2030-2050)	**5.** -8% energy intensity (2030- 2050)

* Targets as calculated using the EU calculation formula.

3.1.3. Critical issues, Challenges & Research questions

All three scenarios described in the previous section envisage an energy system with a large penetration of RES. However, several challenges emerge both in creating a promising safe business case for investors, which are the principal entities for the achievement of the respective RES capacity targets, and for the safe operation of the energy system once these targets are achieved. Thus, one of the solutions to overcome this challenge should be dedicated to the design of markets, which would increase the competitiveness of RES technologies, and enable their participation in the wholesale market, what until today was not possible due to their non-dispatchable nature (Kraan, Kramer, & Nikolic, 2018). This could also reduce the cost of RES integration which is considered a key point for those technologies, which will dominate the new electricity system (Szabó et al., 2019).

In the subsections below, we cluster the main research questions that the SENTINEL models will attempt to provide answers to, as specified through our research approach, under **seven priority areas**, presented in **Table 5**. Providing answers to these research questions is crucial for the energy transition to a sustainable, RES-dominated energy system in Greece. Each thematic priority area is discussed below in detail, along with a series of contextual critical issues and challenges, and relevant specific research questions. Selected findings are presented verbatim in quotation marks, using a code[8] to indicate a different stakeholders' background directly to the contextual critical issues/ challenges and research questions, as discussed during the physical group sessions and the online interview meetings.

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[8] **NGO:** Representatives from NGOs
IND: Representatives from energy industry
POL: Representatives from policymaking
SRC: Representatives from the field of science, research and consultancy

Table 5. Seven thematic priority areas, as identified and validated by literature review and stakeholder engagement for the National level case study in Greece.

1. **Energy resource planning with a focus on security of supply**
2. **Distributed generation, storage & curtailment**
3. **RES business models**
4. **Direct and indirect electrification & energy efficiency**
5. **Demand-Response & digitalisation**
6. **Environmental impacts**
7. **Socioeconomic aspects & implications**

3.1.3.1. Energy resource planning with a focus on security of supply

The ability to maintain long-term security of electricity supply is deemed as one of the main challenges of the low-carbon transition (Liebensteiner & Wrienz, 2019). As stated by stakeholders, “*the process of energy resource planning should not only incorporate economic models, but also detailed technical models for the proper analysis of the operation of the power system under high RES penetration* (**SRC**)” and, specifically, “*more detailed technical parameters should be considered, beyond the limitations of conventional units, like ramp rates, issues like voltage regulation, reactive power, and system stability*” (**IND**).

RQ1. Does planning long-term transition pathways for a decarbonised energy system account for capacity adequacy and security of supply (Antenucci, Crespo, Gjorgiev, & Sansavini, 2019)**?**

Trade-offs between lignite-fired and gas-fired power plants

Where we are

The majority of the lignite-fired generation units (GU) will be decommissioned by 2023 in all the energy scenarios specified, even though “*there is some critique that the fast shut down of lignite plants gives too many advantages to natural gas plants”* (**IND**).

Where we want to get to

However, the increasing EU Emissions Trading System’s (ETS) carbon prices and the large penetration of RES GU envisaged in all the scenarios, may lead to natural gas GU becoming gradually less competitive in the wholesale market, limiting their contribution to the electricity mix (Ministry of Environment and Energy, 2019b). “*Many investments in natural gas units could be stranded assets, since in 10-15 years they will be in the same position as lignite plants today”* (**NGO**). Also, “*electricity generation from natural gas will be gradually reduced from 2020 to 2030, and electricity will be generated only by the new natural gas plants to be installed in the current decade.*

RQ2. “Should natural gas plants, which will start operating after 2025, be shut down after 2035? What should the time horizon of gas as an intermediate fuel towards decarbonization, in financial terms, be?” (IND).

How to get there

Main prerequisite for the reduction of electricity generation from natural gas is the sudden increase of the EU ETS carbon price, which should continue operating as a policy measure, since other measures do not exist or are not consistent (e.g., RES tenders, etc.)” (**IND**).

RQ3. What is the expected contribution of fossil fuels (*RF*: 19.13 TWh (2030), 9 TWh (2050), *RE*: 0 TWh (2050), *P2X*: 0 TWh (2050)) **in the electricity mix in view of the "de-lignitisation" (i.e., lignite phase-out) of the Greek power system?**

RQ4. "Will EU ETS carbon price policies be sustainable in 2030? Should other strategies besides the EU ETS carbon price be considered so that natural gas can be the intermediate fuel that period?" (IND).

Trade-offs between thermal and RES capacity under system constraints

Where we are

A possible answer to the question "*How does the system respond during hours of high variable RES penetration?*" could be given by analysing recent events. "*During the 1st of May 2020, the system had for the first time for four consecutive hours zero marginal price. This means that installations which produced during those hours will not be paid the differential increment for the energy they produced. These incidents should be included in the modelling, since it is expected that they will appear more frequently as RES penetration increases. It will be interesting to see the way the system operated during the low demand-high RES generation periods: which units increased their generation when wind generation decreased? Was it hydro plants? What was the strategy of the system operator when wind generation decreased?*" (**IND**).

Where we want to get to

The increased share of RES is likely to challenge the capacity of systems to maintain security of electricity supply (Solomon, Bogdanov, & Breyer, 2019). The energy industry is still sceptical on the issue of high RES penetration, as stated by one interviewee "*RES penetrations higher than 60% are overly ambitious and long term*" (**IND**). However, there is optimism in the industry as the same interviewee mentioned that "*within some years variable RES plants will be operated like conventional plants are operated today*" and "*large wind turbines (above 5MW) can already offer services comparable to those of conventional units*" (**IND**).

How to get there

Regarding future bidding offers and capacity investments, a stakeholder added that "*when the system reaches 65% penetration of RES electricity, as foreseen by the current NECP, it would be difficult for investors to bid if they do not have a portfolio of variable RES, thermal power plants and storage, so that they can securely offer their bid if the forecast of variable RES generation is not correct. Acceptable RES penetration levels are those, that considering the capacity factors of RES, the weighted average cost of capital for RES investments is comparable to that of the conventional units*" (**SRC**). In this respect, the interdependencies between electricity and gas networks, i.e., the use of gas-fired generation units for balancing the volatility of RES, should be considered with regards to security of supply (Antenucci et al., 2019). As suggested during physical meetings with stakeholders (Tier 2), "*natural gas units should be kept for grid security reasons and in a longer-term horizon, natural gas units are expected to remain in operation as balancing units*" (**IND**).

RQ5. How much thermal (*RF*: 6.91 GW (2030), 6.5 GW (2050), *RE*: 4.9 GW (2050), *P2X*: 7.9 GW (2050)), **and RES capacity** (*RF*: 19 GW (2030), 26.5 GW (2050), *RE*: 33.9 GW (2050), *P2X*: 63.8 GW (2050)) **would be needed in 2030 and in 2050 to meet demand requirements with an aim to maximise RES penetration?**

In a system with high RES penetration and without lignite-fired power plants, the access to system reserves will become a challenging task (Statnet, Energinet.dk, Svenska Kraftnat, & Fingrid, 2016; Yin, Wang, & Qiu, 2019). This is due to the fact that increased RES penetration increases the intermittency and planning complexity of the system, and "*the proper and stable operation of the power system under high RES penetration should be ensured providing adequate reserves and the option for storage*" (**SRC**). However, "*in* *case of high RES penetration, it is difficult to calculate the flexibility of power plants and systems (i.e., upper, lower reserves requirements and storage). Furthermore, the higher the RES penetration, the higher the residual load volatility to be met by dispatchable power plants is" (***SRC***).*

RQ6. Can the gas-fired generating resources and imported electricity meet the demand (*RF*: 61.8 TWh (2030), 80.3 TWh (2050), *RE*: 100.9 TWh (2050), *P2X*: 173.2 TWh (2050)), **and system reserve requirements in case of large RES penetration** (*RF*: 38.1 TWh (2030), 68 TWh (2050), *RE*: 97.5 TWh (2050), *P2X*: 169.8 TWh (2050))? **What would the role of fast and flexible units as system stabilizers be**?

RQ7. As RES penetration in the distribution system increases, what will be the necessary actions for dealing with RES intermittency in the context of market operation?

RQ8. How will the decommissioned lignite-fired capacity and the added RES capacity affect the cost of emissions and the system marginal price (Abbott & Cohen, 2019)**? What is the necessary total investment cost for the added RES capacity and what is the total system cost? What are the specific economy-wide effects of the lignite phase-out?**

The role of electricity interconnections

Where we are

A stakeholder highlighted that "*electricity interconnections is a crucial parameter for the decarbonisation of the power system, as they offer the possibility to transfer easily large quantities of energy between countries. The Greek system, however, is lacking in this respect*" (**SRC**).

Where we want to get to

With regards to interconnections another stakeholder stated that "*a big question regarding energy resource planning is how electricity markets will work in an integrated manner under the Target Model. Will generators tend to sell electricity at a low price to countries with higher electricity prices?*" (**SRC**). Some domestic network upgrades will be necessary under a high RES penetration, and interconnection strengthening with neighbouring countries may play a significant role in the security of power supply (Committee on Climate Change, 2019). As also stated during the online interviews, "*it is necessary to a have higher capacity and better interconnections with the neighbouring countries*" (**SRC**), and "*planning exercises should consider the need for adequacy of power supply through interconnections. The assumptions used in the different scenarios for the interconnections after 2030 are critical for the system operation*" (**IND**).

How to get there

Cooperation with neighbouring countries can reduce the cost of system decarbonisation since interconnected countries could also exploit RES electricity exports in cases of high RES penetration. The problem with network upgrades is their high investment cost (Szabó et al., 2019). The Greek NECP explicitly underlines this problem and suggests that regulations which will ensure return of investment (ROI) should be in place, to increase the attractiveness of network upgrade projects (Ministry of Environment and Energy, 2019b).

RQ9. With what level of return of interest (ROI) should measures be designed (i.e., grid levies) to make network upgrades viable?

RQ10. What is the contribution of interconnections (RF: 4.58 TWh (2030), 3.4 TWh (2050), RE: 3.4TWh (2050), P2X: 3.4 TWh (2050)) **to the operation of the Greek power system under high RES penetration? What level of power independency could be achieved?**

Placement of RES installations

Where we want to get to

For large RES projects, improper placement of RES installations could introduce saturation problems to the electricity grid and jeopardise the availability of reserves (Statnet et al., 2016). The placement of new installations by simultaneously considering network constraints and the RES potential of certain regions might be a challenge (Committee on Climate Change, 2019).

How to get there

As mentioned also during the stakeholder consultation, “*the spatial distribution of RES in the case of extremely high penetration is a critical issue. We should explore proper land planning options to ensure an acceptable geographical distribution*” (**IND**). Furthermore, for the case of Power Purchase Agreements (PPA), large RES projects should be sited close to large consumers to ensure the viability of the business model (Psomas, 2019).

RQ11. What factors should be considered to determine the geographical siting of large RES projects used to replace conventional power in terms of minimising system losses and costly network upgrades?

RQ12. Which regions in Greece are candidates for a PPA business model?

3.1.3.2. Distributed generation, storage & curtailment

Storage options

Where we are

According to stakeholders, “*natural gas plants with storage are a barrier to the technology adoption of RES storage technologies*” (**IND**). In the case of high RES penetration in the electricity system, storage systems are needed (Nanaki & Xydis, 2018) to manage variable RES generation, as the flexibility needs of the power system increase (Ministry of Environment and Energy, 2019b; Solomon et al., 2019). With regards to pumped storage, “*such options exist in Greece, since we already have a number of hydro plants”* (**SRC**).

Where we want to get to

Pumped storage technologies should be combined with battery storage options” (**IND**). Storage systems could help absorb more RES electricity, enabling RES, which have high intermittency (Tröndle, Pfenninger, & Lilliestam, 2019) to become the main source of energy (Ministry of Environment and Energy, 2019b). As mentioned by a stakeholder, “*it is very difficult to reach a 100% RES system without storage and without improving the technical capacities of storage systems. Conventional units will be needed for reserve requirements*” (**IND**). “*After 2030, hydrogen can be a more preferable way of storage than batteries in remote or non-interconnected electricity systems if there is a natural gas network or a port nearly. In cases of high RES penetration, energy conversion to hydrogen via sector coupling starts having greater value. Hydrogen production can be an alternative to electricity grid expansions. It is possible that remote or non-interconnected sites can be deployed for hydrogen production*” (**IND**).

How to get there

Storage could either be aggregated, considered as a virtual power plant with a centralised scheduling, or it can be installed in homes and offices as a decentralised option (Castagneto Gissey, Subkhankulova, Dodds, & Barrett, 2019). According to stakeholders, “*if curtailment is very low and distributed storage is not economically feasible, centralised storage can be selected*” (**IND**). Still, “*the lack of central system control with dispersed generation systems is one of the main problems”* (**IND**). Literature suggests that centralised scheduling is less costly than a decentralised option (Castagneto Gissey et al., 2019). However, “*a regulatory framework for storage is lacking and should be introduced soon*” (**IND**).

RQ13. How much RES capacity and storage (RE: 22.4 TWh (8.5 GW) (2050), P2X: 42.4 TWh (28.1 GW) (2050)) **are needed to reach a 100% renewable energy electricity mix (RE and P2X scenarios)**

without excessive curtailment? How does RES capacity relate to RES generation and storage needs (Solomon et al., 2019)**? What is the cost of each additional percent of RES generation injected to the system?**

RQ14. How is the foreign trade of electricity affected when storage technologies are deployed?

RQ15. Which option (i.e., decentralised or centralised scheduling of storage) is cost-optimal for the Greek electricity system?

RQ16. Could distributed RES systems and community scale virtual power plants (e.g., in non-interconnected islands) facilitate achieving electricity independence? Which criteria should they fulfil to become electricity-autonomous (McKenna, 2018)**?**

Curtailment implications regarding the interconnected system

Where we are

When the system's safe operation limits are expected to be violated with additional RES generated electricity, a portion of RES electricity is curtailed, i.e., generation is reduced due to technical constraints of the electricity system. While curtailment is a proven method for managing excess RES generation (Solomon et al., 2019), it entails financial burdens for producers, which do not utilise the full potential of their systems, and, thus, should not be applied extensively (Michas, Stavrakas, Spyridaki, & Flamos, 2019).

Where we want to get to

"After 2030, there will be high levels of curtailment due to the high RES generation levels compared to the demand at specific hours and the incapability of meeting demand using imported electricity as well as there will be no priority RES generating units (e.g., generators currently under the Feed in Tariffs (FiT) scheme)" (**IND**).

How to get there

Overall, "*the level of curtailment is really a function of RES penetration in the system. Curtailment could be due to dynamic stability issues (the instantaneous RES penetration cannot be more than a certain limit) and due to the technical minimum of conventional power plants already in the system. These two factors will determine the need for reserves and storage. Variable RES generation can be converted into dispatchable generation using storage resulting in minimum curtailment* (**SRC**). *"Curtailment should be found at the national level and then downscaled at project level. The resulting curtailment percentage could be the driver to storage, but according to the latest study on the need for storage in the system, curtailment by itself is not a sufficient driver for the installation of storage systems*" (**IND**). Another stakeholder argued that "*storage can be an efficient method to minimise the level of curtailment*" (**SRC**).

RQ17. What is the maximum RES penetration (defined as system limit) that could be accommodated within the Greek electricity system with acceptable levels of curtailment? Curtailment should not surpass the 5% threshold, according to the EU regulation (European Parliament and the Council, 2019)**.**

RQ18. With the achievement of the NECP's targets, i.e., 7 GW of wind and 7.7 GW of PV installed, what is the expected level of curtailment with and without storage technologies?

"*If the cost of curtailed energy is also paid then the end cost for the consumer would be high*" (**SRC**). In this case "*What is the cost of electricity in the case of extremely high levels of variable RES penetration?*" (**SRC**).

RQ19. What economic impact on individual investors and economy-wide level does curtailment have, considering curtailment compensation schemes?

One of the stakeholders wondered "*what is the optimal capacity ratio of wind turbines and solar PV?"*, adding that *"this capacity ratio is case specific, as it depends on the geographical siting of the technologies*" (**IND**).

RQ20. What is the optimal wind/ PV ratio to achieve maximum RES penetration with low curtailment with and without storage technologies?

Curtailment implications regarding the non-interconnected islands

Where we are

Non-interconnected islands generate electricity using fossil fuels at high cost.

Where we want to get to

In case RES capacity increases significantly, a key challenge will be the mitigation of curtailment, especially in non-interconnected islands, where its effects have not been researched thoroughly (Song et al., 2018).

How to get there

RES combined with energy storage could be a solution for the electricity independency of islands (Nanaki & Xydis, 2018), while interconnection of islands could be an alternative solution. For instance, the island of Agios Efstratios should achieve an 85% level of RES penetration until 2030 (Ministry of Environment and Energy, 2019b). According to an interviewee, "*the operation of the system of Crete can offer significant know-how for the operation of the interconnected system under high RES penetration. Currently, in the control area of Crete each wind park has a set point, which determines the amount of electricity that it can provide, ensuring that the system balances. RES curtailment is of the order of 8-10%, which is acceptable and is agreed with the RES producers*" (**SRC**). On the other hand, "*the power system of Rhodes has very high curtailment levels, which could be reduced if RES producers created a central storage unit"* (**NGO**).

RQ21. How much RES capacity and storage does a representative non-interconnected island require to reach power independence with 100% RES?

RQ22. What are the energy and power storage needs considering the reserve capacity requirements in a RES-based Greek interconnected system?

3.1.3.3. RES business models

Where we are

As RES capacity increases, each RES producer will aim at maximising profits, thus, the selection of the most economically attractive business model will be of primary importance. Regarding net-metering, stakeholders noted that "*net-metering has been very profitable and the directive for the internal market in electricity mentions that injected energy will be metered at the wholesale price, instead of the retail price after 2023. Net-metering is expected to be lifted, since it is considered a distortion. Even though net-metering could be very profitable if implemented in the tertiary sector, its potential has not been exploited yet. This is due to dimensioning mistakes, as, initially, attempts to cover 100% of the yearly needs of the enterprises were made instead of maximising the simultaneity of production and consumption*" (**IND**).

Where we want to get to

For the case of participation of RES in the wholesale market, RES technologies have low operation and maintenance (O&M) requirements (Michas et al., 2019), and, thus, much lower variable costs compared to conventional GUs. In this regard, "*the cost of GHG emissions in the future will balance the cost of production from RES. In the long run the cost of electricity is expected to be reduced because of RES penetration, which will be a direct benefit for consumers*" (**SRC**).

How to get there

Investments in RES depend on the attractiveness of the applied business models (Vassilis Stavrakas, Papadelis, & Flamos, 2019). The level of RES investments/ adoption should be steady and continuous, rather than abrupt to avoid sudden consumer-scale electricity price impacts (Szabó et al., 2019). Furthermore, even if new business models tend to be subsidy-free (Psomas, 2019), when state support is included in a business model (i.e., FiP contract), the liquidity of the RES special account should be considered during the design of the support level in order to avoid deficits, such as the one occurred with the introduction of Feed-in Tariffs (FiT) during the period 2008-2013 (Koumparou, Christoforidis, Efthymiou, Papagiannis, & Georghiou, 2017; Kyritsis et al., 2017; Vassilis Stavrakas, Kleanthis, & Flamos, 2020). Legal issues are also important, e.g., "*the existing legal framework for small PV systems is rather complicated and does not contribute to the wider penetration of the technology*" (**NGO**).

RQ23. What are the expected RES adoption rates under different business models? Do novel business models (i.e., leasing, sale and lease back) attract risk-averse consumers' investment interest?

RQ24. How does the resulting electricity mix affect the levelized cost of electricity (LCOE) under different RES business models? Which RES adoption rates should be followed to avoid negative consumer price impacts?

RQ25. When state aid is provided to RES projects, what is the level of support (e.g., subsidy levels) that should be awarded in order to avoid deficit in the RES special account (i.e., caps in the tendering process)?

Challenges may also arise regarding the choice of the operational aid scheme for RES. As mentioned in the "Renewable and Storage Forum 2019" that took place in Athens (Psomas, 2019), with the application of the EU target model in the Greek electricity market, RES producers will have three business cases for supplying their produced electricity: **(i)** a Feed-in Premium (FiP) contracts, which will be awarded via a technology-neutral tendering process, **(ii)** participation in the wholesale market, possibly represented by RES aggregators, and **(iii)** power purchase agreements (PPA) with energy consumers for direct electricity trading.

RQ26. What are the expected economic benefits of these business models for each RES producer category (small-scale, large-scale, aggregators)?

For small-scale, decentralised RES projects, and particularly PV, self-consumption models shall emerge where prosumers consume most of the electricity generated at local level and sell the excess to the grid. The main challenge of decentralised generation and prosuming is that the initial cost of RES technologies may be prohibitive for investments, despite the benefits over the investment's lifetime. This fact is even more obvious in the case of economically vulnerable consumers (Ministry of Environment and Energy, 2019b; Nanaki & Xydis, 2018). *"Leasing models will be offered to the consumers by the electricity providers/ utilities, which will have the central storage systems and act as aggregators. In this regard, it is probable that there will be no prosumer model*" (**IND**).

RQ27. What are the benefits for prosumers under a self-consumption scheme over the investment's lifetime? What financial business models (e.g., leasing) could be applied to reduce the high initial investment cost, and what business models could increase chances of prosumers investing in RES projects (Bauknecht, Funcke, & Vogel, 2020)**?**

3.1.3.4. Direct and indirect electrification & energy efficiency

Electrification of the transport sector

Road transport: Electric mobility

Where we are

"Currently, there are several barriers to electric mobility that should be overcome" (**NGO**). The high initial investment cost of electric vehicles (EVs) could be an impeding factor to their dissemination. Furthermore, for the case of EVs, even though most drivers charge their EVs at home, their limited range autonomy means that the lack of appropriate charging infrastructure will pose a further problem for the promotion of the technology (Ministry of Environment and Energy, 2019b).

Almost 85% of EVs' users charge their vehicles at their residence (A Perellis, Mezartasoglou, & Stambolis, 2018). With the current average carbon emissions for electricity generation in Greece (Alexandros Perellis & Stambolis, 2018), full electrification in road transport would result in more than 5 Mt $CO_{2,eq}$ of annual indirect emissions, which is far from carbon neutrality. An important factor for this situation is the low contribution of RES to the transport sector in Greece, which is still low, i.e., only 1.4% in 2016, placing the country 3rd from last among the EU member states (Tuszyńska, 2018).

Where we want to get to

Except for the projections made by the Greek NECP, other projections found in the literature show that EVs' penetration in the Greek transport sector could reach 3,500 EVs until 2020, 8,000 EVs until 2025, and 15,000 EVs, as well as 90 electric buses until 2030, as a result of the applied program for public transportation (A Perellis et al., 2018). It is also estimated that the penetration of 10,000 EVs in the Greek transport sector would result in an additional 17.6 GWh annual electricity demand and an additional annual peak demand of 0.92MW (Alexandros Perellis & Stambolis, 2018).

If a full electrification of the Greek road transport occurs, more that 5 million internal combustion vehicles (ACEA, 2018) will be substituted with electric ones resulting in more than 8,800 GWh annual additional load in the electricity system. Moreover, "*the electrification of transport is expected to change completely the form of the load curve*" (**IND**). On the demand side, the imbalance between RES generation and demand is a major technological challenge and makes the contribution of RES to transport a challenging task (Nanaki & Xydis, 2018).

RQ28. What are the additional electricity consumption patterns resulting from the electrification of the transport sector (RF: 278,254 EVs (2030), 6,029,000 EVs, RE: 8,011,000 EVs (2050), P2X: 7,607,000 EVs (2050))**? How could 'smart charging' (e.g., charging overnight) influence these patterns and to what extent can charging costs be avoided** (Committee on Climate Change, 2019)**?**

RQ29. How would the electrification of the transport sector affect the electricity mix? Are there increased needs for reserves and what is the role of imports due to the increased peak demand? What are the expected effects on electricity prices?

RQ30. With increased aggregated penetration of RES, what would be the resulting share of RES in transport with the current EV charging patterns?

How to get there

RQ31. What adoption rates of EV are expected under different business models (i.e., using car batteries) as system reserves during stationary hours, leasing schemes to reduce initial investment costs for EVs, subsidies? If these business models were used, when would cost parity between EVs and conventional vehicles happen?

RQ32. Could heavy goods vehicles (HGV) and electric motorcycles be effectively decarbonised using batteries under their technical requirements (i.e., weight, cargo and autonomy)?

It should be considered that "*EV charging projects are considered as projects of common interest (PCI), and, thus, will receive low interest loans from the European Investment Bank (EIB). They may be state aid eligible projects (i.e., eligible for grants and subsidies). Two key parameters for these projects are charging time and* *kilometre range of vehicles. There is a risk of over-dimensioning charging stations in case these parameters are not considered*" (**IND**). "*The option of replacing batteries with fully charged batteries in a station (operating like today's gas stations) would be an interesting business model when the technology is available*" (**SRC**).

RQ33. What are the charging infrastructure requirements, and their cost, when 100% electrification of road transport is achieved?

Road transport: Mobility with hydrogen

How to get there

Gasification could be considered as a form of indirect electrification, as electricity is used in order to produce synthetic fuels, which are used for the road transport (Ruhnau, Bannik, Otten, Praktiknjo, & Robinius, 2019). Indirect electrification is a fuel synthesis process, which results either in hydrogen through electrolysis or synthetic methane through methanation (Ruhnau et al., 2019).

RQ34. To what extent could indirect electrification displace direct electrification in the transport sector?

RQ35. Could heavy goods vehicles (HGV) be effectively decarbonised using hydrogen under their technical requirements?

Shipping

Where we want to get to

Ammonia and hydrogen are the state of the art low-carbon technologies that could be used in shipping. Ammonia is less expensive to store as a liquid than hydrogen regarding both technical (e.g., cryogenic conditions) and cargo displacement requirements. However, hydrogen is highly flammable and ammonia is toxic, thus, safety regulations should be structured regarding their use (Committee on Climate Change, 2019). As stated during the stakeholder consultation, "*hydrogen could play a complementary role in transport, especially in ships, since it is difficult to have electric vessels or electric planes*" (**IND**). Another barrier in shipping is that the ships are often chartered, thus owners do not prioritise fuel efficiency as fuel costs are typically paid by the charterer (Committee on Climate Change, 2019).

RQ36. What are the possible adoption rates of ammonia and hydrogen technologies in the shipping sector?

How to get there

RQ37. What business models could be used to trigger investments in low-carbon technologies in the shipping sector while maintaining owners' profits at a sustainable level?

Electrification of the heating sector & energy efficiency

Electric heating and cooling

Where we are

Barriers such as the high investment cost of heat pumps or lack of expertise in designing and installing them could be impeding factors to their dissemination (Calderón, Underwood, Yi, Mcloughlin, & Williams, 2019). Synergies between RES (especially PV) and heating and cooling (i.e., solar-assisted heat pumps) have been studied in literature as a means of reducing the cost and energy requirements of heating and cooling applications (Michas et al., 2019). Apart from the high initial investment cost, in many buildings a lack of suitable space further inhibits the installation of adequate PV capacity, particularly in more-developed urban areas. At the same time, EE investments could reduce the heating and cooling needs of a building, thus, reducing the PV capacity needed to achieve these synergies.

Where we want to get to

Electrification of heating and cooling in Greece is expected to be greatly enhanced with the use of heat pumps. Specifically, until 2050, heat pumps are expected to be installed in 853,000, 3,197,000 and 828,000 residential buildings, in line with the RF, RE, and P2X scenarios, respectively (Ministry of Environment and Energy, 2019a). However, if a large number of heat pumps were to be operated at the same time alongside the overnight charging of EVs, there would be a significant load requirements (Pimm, Cockerill, & Taylor, 2018).

RQ38. What are the additional electricity demand patterns and the effect on peak load demand resulting from the electrification of the heating and cooling sector?

RQ39. With increased aggregated penetration of RES, what would be the resulting share of RES in the heating and cooling sector with and without electricity storage (RF: 42.5% (2030), 52%, RE: 80% (2050), P2X: 92.9% (2050))?

RQ40. How would the electrification of the heating and cooling sector affect the electricity mix? Are there increased needs for reserves and what is the role of imports due to the increased peak demand? What are the expected effects on electricity prices?

How to get there

RQ41. What adoption rates of heat pumps are expected under different business models (i.e., solar-assisted heat pumps, Energy Performance Contracts (EPC) for heat pump installation)?

RQ42. How are life-cycle costs of heat pumps affected when services (i.e., load shifting) are offered to the grid?

RQ43. What kind of policies could promote the adoption of heat pumps (and other EE measures) by improving the economic viability of the technology (e.g., carbon tax) (Costello, 2018)**?**

RQ44. How much GHG emissions reduction could result from the adoption of heat pumps in the heating sector, and what would the macroeconomic implications be?

A challenge is to find the optimal balance of EE investments and PV capacity installation (Attia et al., 2017) to achieve cost effective synergies of PV with the heating and cooling sector, while also respecting space restrictions.

RQ45. What are the optimal EE and PV investments in buildings in order to achieve cost effective synergies between RES and the electrified heating and cooling sector? What are the rebound effects due to behavioural consumption patterns?

Heating and cooling via hydrogen

How to get there

Hydrogen could provide low-carbon energy at peak demand, substituting natural gas in the industry sector. As stated by an interviewee, "*hydrogen will be mainly used in industry*" (**NGO**), however, "*heat recovery is a technology option which should be explored before we move on to the next step of hydrogen economy*" (**POL**). Industrial equipment usually has a long lifetime, therefore, the potential for adoption of new technologies may be limited in cases, where previously installed equipment is to be deployed until the end of its lifetime, Stakeholders during physical meetings mentioned that "*the replacement of natural gas for industrial uses would be a difficult part of decarbonisation*" (**IND**). Nevertheless, existing equipment could be adapted for alternative use (e.g., hydrogen gas boiler for space heating).

RQ46. To what extent could gasification displace direct electrification in the heating sector?

RQ47. What are the technical barriers regarding the use of hydrogen for industrial heating applications?

RQ48. How is the technology adoption of new assets influenced by the lifetimes of previously installed equipment in the industry sector?

RQ49. Which mechanisms could promote investments in CCS and hydrogen technologies in the industrial sector?

Energy Efficiency

Where we are

According to the NECP, selecting cost-effective applications, simplifying the existing processes, the lack of incentives for EE measures, and the difficulty in implementing EE projects via innovative financing schemes (e.g., EPC) can be barriers to the exploitation of existing funding mechanisms (Ministry of Environment and Energy, 2019b). Regarding challenges for the implementation of EE projects, a stakeholder mentioned, "*there are no energy service companies (ESCOs) in Greece. There is a need for setting up loan schemes for EE interventions, which could support the creation of ESCOs, maybe under European Investment Bank (EIB) activities*" (**NGO**).

Where we want to get to

With regards to EE obligation schemes, which are the most widespread market mechanism and can lead to the implementation of cost optimal EE measures, the transitioning from behavioural to technical measures as well as expanding the scheme by trading certified energy savings are considered as main steps towards the mainstreaming of EE projects (Ministry of Environment and Energy, 2019b). As stated during the stakeholder consultation, "*subsidisation with obligation compliance for the upgrade of energy consumption could be a key incentive for energy efficiency"* (**NGO**).

RQ50. Which EE measures are the most cost-efficient with regards to the available funding mechanisms and which measures can lead to maximisation of energy savings?

Furthermore, "*the amount of funding which is offered for residential building renovations should be increased. It is necessary to have on an annual basis two programs of the level of "Exoikonomo 2", corresponding to something like 1 billion Euros per year to achieve the EE targets. Incentives should be provided to companies for upgrading their buildings as well*" (**NGO**).

How to get there

The new "*Exoikonomo- Aftonomo"* programme, deriving from the EU Recovery Fund, a mechanism to mitigate COVID-19 effects, can facilitate the sustainability of household refurbishments in the residential sector (Hellenic Ministry of Environment and Energy, 2020).

RQ51. "*What should be the level and the timing of financing in combined RES and EE measures in different types of buildings of the residential sector in the framework of the "Exoikonomo- Aftonomo" programme*" (POL)?

RQ52. "*Which and how many households should receive funding in order to reach the specified targets with the least possible costs*" (POL)?

3.1.3.5. Demand-Response & digitalisation

Where we want to get to

For a sustainable energy system with high electrification and high RES penetration, load management and energy storage will be required alongside flexible conventional generation methods (Agora Energiewende, 2015; Nanaki & Xydis, 2018). "*Regional control services can contribute to a better operation of the system offering a control area at the level of neighbourhoods. Remote measurement in the demand sectors is necessary to obtain a clear picture of the load which should be managed*" (**IND**). Optimally integrating RES and heating and cooling installations is an explicit need, mentioned in the Greek NECP (Ministry of Environment and Energy, 2019b).

Digitalisation (e.g., smart meters, RES aggregation, virtual power plant management, etc.) would enable better system management and create opportunities for active consumer participation (e.g., prosuming, demand-response, etc.) (Statnet et al., 2016). "*The installation of smart meters will have an added value for the consumers, but the cost will be paid by them. It would be useful if part of the cost of smart meters was funded, to deploy them widely as soon as possible. Financial incentives should be created by the utilities to maximise the advantages of smart meters (i.e., time of use tariffs or even more adaptive tariff schemes, which could contribute to the smoothening of peaks)*." (**NGO**). Overall, "*proper demand-response with the use of smart meters can achieve the necessary peak shaving in the system operation*" (**IND**). Furthermore, "*towards digitalisation, a software which monitors data and calculates the CO_2 emissions per type of energy and the total CO_2 emissions per period could be very useful for consumers. Digital platforms with user-friendly interfaces for consumers could benefit generators with regards to demand management*" (**NGO**). Internet-of-things (IoT) and smart buildings are notions related to digitalisation and through it to demand-side management options.

How to get there

With the wider implementation of storage and digitalisation, a bigger part of the additional electricity demand stemming from the electrification of the heating and transport sectors could be covered through RES generated electricity (Nanaki & Xydis, 2018). According to a stakeholder, "*demand-response is competitive to storage. It is desirable to combine these technologies*" (**IND**). However, one of the interviewees argued that "*demand-response or demand-side management, in general, is not expected to cause large changes to the needs for investments in storage installations*" (**SRC**).

RQ53. To what extent could demand-response technologies limit the need for costly storage installations and increase the system's flexibility?

RQ54. What are the costs and benefits of combining electricity storage with demand-response technologies and how are these benefits distributed between actors in the electricity supply chain? What financial incentives should be applied to attract consumers' participation?

Indicative business models include: **(i)** Peer-to-Peer (P2P) energy exchanges, whereby consumers can buy stored electricity locally from prosumers, which store their excess electricity (Brown, Hall, & Davis, 2019), **(ii)** Prosumer-to-Grid (P2G), whereby prosumers consume their own energy, as required, store and sell their excess generation to the rest of the grid, and **(iii)** Organised Prosumer Groups (OPG), where the benefits of the above two business models are combined; prosumers sum their generation and storage and act collectively (which could be considered as RES aggregation with local virtual power plant). In the case of EVs, the Vehicle-to-Grid (V2G) business model resembles the P2G model mentioned above; the prosumer charges his EV with RES generated electricity and uses the vehicle battery to cover household needs during stationary hours (Brown et al., 2019; Michas et al., 2019).

RQ55. How do different RES/ storage business models (i.e., P2P, P2G, OPG) perform in terms of profit for different actors? What are the respective governmental costs, if any?

RQ56. What levels of RES penetration could be achieved through the use of the V2G business model in the residential and transport sector?

Literature states that the high expected growth of EVs' sales could be a challenge to the grid, especially when combined with ongoing increases in battery capacities and charging rates. Grid-to-Vehicle (G2V) and V2G models could also be used in order to increase the flexibility of a smart grid. Aggregation of a large number of EVs and the management of their G2V and V2G energy flows as a virtual power plant could also be a significant challenge (Pereirinha et al., 2018). "*Utilities could contribute to the deployment of charging stations. Consumers will have a flat tariff for a variety of electricity usages including EVs' charging. EV charging stations could operate as aggregators or utilities and could regulate the timing of charging. This could be the initial structure of the V2G model. This market will concern only big companies/ investors.*" (**IND**).

RQ57. How is the initial investment cost of EVs affected when services (i.e., load shifting, covering of household needs with car battery) are offered to the grid?

RQ58. What is the optimal combination of V2G and G2V models so that load 'peaks' and 'valleys' are smoothened effectively? What other effects could V2G and G2V cause to the electricity system? Could smart-charging contribute to peak shaving?

RQ59. How much (vehicle/ stationary) storage is needed to achieve 100% RES absorption (with minimum curtailment) in the Greek electricity system when the transport sector is fully electrified? What is the maximum peak shaving that can be achieved with the use of different types of storage (i.e., vehicle/stationary) (Pimm et al., 2018)**?**

3.1.3.6. Environmental impacts

Policymakers, as well as civil society organisations, are deeply concerned about the environmental impacts of energy systems transitions. "*Environmental impacts should be addressed in modelling exercises, with the introduction of externality costs. This would differentiate the prioritisation of investments based on, firstly, their environmental and, secondly, their social impact. The process should aim in choosing the best way for achieving social prosperity*" (**POL**). Therefore, the ability to incorporate environmental factors into the energy planning process, especially in the case of extreme decarbonisation scenarios, is crucial.

GHG emissions' evolution

Where we are

The average GHG emissions from electricity generation in Greece were 582 g CO_2/kWh in 2015 (Alexandros Perellis & Stambolis, 2018), which is relatively high, due to the dominance of fossil-fuelled power plants in the electricity mix.

Where we want to get to

The GHG emissions reduction targets have been presented in all scenarios in **Section 3.1.2**.

How to get there

RQ60. How are the average GHG emissions (by economic sector) expected to evolve in the Greek energy system under different transition pathways (under the RF, RE, P2X scenarios)?

RQ61. How are the average GHG emissions of the Greek electricity system expected to evolve under high RES penetration and reduced contributions from conventional GUs? What are the macroeconomic implications?

RQ62. Which transition pathways (choice of technologies and deployment timing) for the decarbonisation of the Greek electricity sector are capable of achieving high GHG emissions reduction (Pleßmann & Blechinger, 2017)**? Which of these pathways are low-cost?**

Power-to-X technologies

Where we want to get to

After the majority of the lignite GUs are decommissioned, gas units will play a significant role in electricity generation in Greece. However, decarbonising these units using carbon capture and storage (CCS) and hydrogen fuel cells is a challenging process. Furthermore, CCS plants are not capable of capturing their total emissions and their capture rates will need to be high enough to avoid high overall emission levels (Committee on Climate Change, 2019). Still, "*CCS technologies have a low technology adoption rate and are very costly*" (**SRC**).

How to get there

RQ63. Could CCS and hydrogen fuel cells be cost-effective options to be considered as GHG emissions mitigation strategies (Wendling, 2019)**? What CO_2 transport infrastructure would be required and what storage capacities would be necessary** (CCC, 2018)**?**

RQ64. Which policies could encourage the adoption of CCS and hydrogen fuel cells systems with high carbon capture rates?

Circular economy/ Recycling

Where we want to get to

"*The quantification of the effects of circular economy is the next important topic to be analysed by modelling tools*" (**POL**). Consideration of the full life-cycle effects of storage technologies has shown that using, reusing, remaking, and recycling batteries is more challenging than simply disposing of them. "*One of the main environmental issues of battery storage is what happens with the batteries at the end of their lifetime. All materials used in energy technologies should be recycled*" (**SRC**). Batteries' disposal is considered not to be environmentally sound, and, thus, unacceptable from a circular-economy standpoint, as batteries can still be used for stationary energy storage after their end of life, and contain valuable materials (e.g., rare earths) that could be recycled (Pereirinha et al., 2018). Other technologies can also be recyclable, for example, "*90% of the wind turbine materials can be recycled. Only their blades are not recyclable, but their material is environmentally neutral and can be used as construction aggregate*" (**SRC**).

RQ65. What are the environmental and economic benefits of exploiting the potential of batteries and other technologies after their lifetime instead of disposing of them, and, in more general, what are the environmental impacts of potential circular economy measures in Greece?

Water issues

Where we want to get to

The study of the metabolism of the energy system can help identify the bottlenecks related to the Water-Emission-Energy (WEE) nexus (Gianpietro, Aspinall, Ramos-Martin, & Bukkens, 2014). Besides environmental impact assessment indicators provided by life-cycle analysis (LCA), indicators of metabolism will be assessed to provide us with a perspective on the systemic impacts.

RQ66. What are the metabolic patterns of the water-energy-emission nexus for the scenarios? What are the main bottlenecks in each of the scenarios?

RQ67. What are the water and carbon footprints of the metabolic patterns for each scenario?

RQ68. What is the level of externalization of resource use and emissions for the scenarios?

Raw material constraints

Where we want to get to

In parallel to the WEE nexus there might be restrictions applying to raw materials and intermediate products (i.e., magnets for wind turbines, PV panels for a solar power plant) due to bottlenecks in the value chain of energy technologies.

RQ69. What is the potential for a supply restriction of raw materials and intermediate products needed for RES technologies?

RQ70. What is the energy return on investment (EROI) and the efficiency of each of the scenarios?

RQ71. Is there any particular RES technology whose potential for implementation is constrained in the short-term?

3.1.3.7. Socioeconomic aspects & implications

Social acceptance issues

Where we are

Socio-technical factors, such as social acceptance of energy technologies, are critical for the transition to carbon-neutral energy systems, since these factors can constrain or accelerate, the pace of diffusion of new technologies. The installation of RES infrastructure, especially wind turbines, introduces several social acceptance issues, related to health concerns, noise, landscape modifications, distributional effects of inadequate economic incentives, and lack of local ownership (Bolwig et al., 2020). "*The success of the energy transition is hindered by the fact that people who live close to RES installations are reacting and they do not directly see the benefits of RES*" (**NGO**).

Where we want to get to

After all, "*it is not easy to change the way people think about renewables and awareness raising campaigns have an effect only if they are spread over longer periods of time*" (**NGO**). Also, "*lobbying against RES has been very successful so far, thus significant efforts should be made to bring change. Campaigns will work only if they are continuous.*" (**NGO**). However, it was reported that "*the Hellenic Wind Energy Association has done a wonderful job in promoting wind energy through publications and awareness campaigns*" (**SRC**).

How to get there

Awareness raising should be combined with incentives since "*the main issue is the lack of incentives towards sustainability. The lack of information is a "secondary barrier"* (**NGO**). Social acceptance could also play a significant role in the technology adoption of CCS technologies (V. Stavrakas, Spyridaki, & Flamos, 2018).

RQ72. What policies (e.g., economic compensation, etc.) could increase the social acceptance of RES and CCS technologies, particularly considering that CCS technologies are not currently deployed in the Greek energy system?

Implications for consumers

Where we want to get to

Furthermore, it is important to understand the ways in which societal actors interact and shape the energy future. Such actors often contribute in far-from-cost-optimal ways, especially in how they react to energy system developments and create pressures that redirect policies and the overall energy trajectory. "*An interesting question to which models could try to provide answers is the willingness to participate in support schemes as a function of the level of subsidies offered*" (**POL**). The way that consumers trade off security of supply and green electricity is also an important social aspect (Merk, Rehdanz, & Schröder, 2019). Consumers both value a higher percentage of renewables in electricity generation and penalize interruptions to supply but "*what would be the effect of energy transition policies to the citizens in terms of energy cost?*" (**NGO**).

RQ73. What are the resulting economic implications for consumers from the trade-off between security of supply and desire for green electricity (e.g., welfare impacts across households)?

In addition to security of supply issues and concern for climate change, the energy sector must also deal with the topic of energy poverty (Uche-Soria & Rodríguez-Monroy, 2020)- the effects of the RES-based transition on vulnerable consumers should always be considered. As was stated during the interviews, "*energy poverty is an existing problem and instead of solving it, new vulnerable groups of consumers might be created, after the shutdown of lignite plants*" (**NGO**). As it was highlighted by a stakeholder, "*vulnerable social groups should be included in the energy transition*" (**NGO**). In this regard, "*How could energy models account for energy democracy and energy justice and what kind of social innovations could facilitate fighting energy poverty?*" (**NGO**).

RQ74. "How could energy models account for energy democracy and energy justice and what kind of social innovations could facilitate fighting energy poverty?" (NGO)

Following **RQ8**:

RQ75. What will be the implications for vulnerable consumers due to the change of the system marginal price and the total system cost (e.g., welfare impacts per income level)?

In addition, also considering **RQ24**:

RQ76. What will be the implications for vulnerable consumers due to the change of the system's LCOE under different RES business models (e.g., welfare impacts per income level)?

In relation to **RQ51**:

RQ77. Which policies could support EE investments in energy poor households (e.g., welfare impacts per income level)?

Just transition and job creation

Where we want to get to

Within a wider social aspect, the implications of the energy transition can span a large landscape. The shutdown of thermal (i.e., lignite, natural gas, etc.) power generation resources, will be at the cost of job losses, especially in regions where the economic activity is largely dependent on fossil resources, since "*it is expected that 4,500 workplaces will be lost due to the shutdown of lignite-fired power plants*." (**SRC**) (Nikas, Neofytou, Karamaneas, Koasidis, & Psarras, 2020). Furthermore, in regions that depend largely on fossil fuels (e.g., the Megalopolis region in Peloponnese, etc.), shutting down of conventional power plants and the consequent reduced operation of mines that supply them with fossil fuels, poses the danger of population desolation.

A post-lignite (and, in general, post-fossil fuel) 'cleaner' development trajectory in such regions should be socially 'just' (Nikas et al., 2020). Therefore, "*it is important to discuss how those who are currently working in the lignite industry will participate in the energy transition. For example, the villages close to the lignite-fired plants could be turned into showcase energy communities*" (**NGO**).

Indeed, the growth of RES technologies will demand human resources. For the transitioning to a RES-based energy system, there will need to be an increase in skilled workers capable of performing the necessary tasks in the energy sector (Rodríguez-Huerta, Rosas-Casals, & Sorman, 2017). Specifically, an increase of 37,400 jobs (22,000 full-time jobs) on a yearly basis is estimated due to the impact of RES penetration and energy upgrading of buildings until 2030 (Ministry of Environment and Energy, 2019b). However, the trade-off with current employment should be also considered.

RQ78. What are the consequences of the energy transition on income and employment, at both the national and the regional level (e.g., NUTS-II, NUTS-III)?

RQ79. What will be the trade-off between current and future employment?

How to get there

"A "Just Transition Fund" should be utilised for the creation of clean energy start-up communities in the areas which are affected by the lignite phase-out" (**NGO**).

RQ80. Which investments towards a clean energy transition trajectory can have a positive impact on employment and income in carbon intensive regions?

RQ81. How does the impact on carbon intensive regions differ from wider national impact?

Energy citizenship

Where we want to get to

An important point that was raised is that *"even though the energy transition will have a positive overall impact, designed policies are not based on citizen needs*" (**NGO**). Energy citizenship is a notion, which is expected to help the transition to a decarbonised future through the shift from centralised fiscal, administrative, and resource management towards distributed governance (Lennon et al., 2020).

RQ82. In case of increased participation of citizens in the energy system, what are the costs and benefits for all the involved stakeholders in social (e.g., welfare distribution), environmental (total CO_2 emissions by economic sector), and economic terms (turnover by economic sectors)?

RQ83. How are the total emissions (by economic sector) expected to evolve in Greece, when the centralised power system transforms into a system with increased participation of decentralised structures (e.g., energy communities, eco-villages, etc.)?

COVID-19 pandemic implications

Where we are

The effects of the pandemic should be studied in detail in order to gain insight on the effects of these unforeseen events on the Gross Domestic Product (GDP) evolution per sector, on the consumption of the different energy commodities, and the corresponding influence of their prices. *"Impacts of the recent pandemic and other unforeseen events should not be neglected, as these situations increase uncertainty" (***NGO***).*

Where we want to get to

*"Resilience plans should be developed for each city separately" (***NGO***).* As mentioned by a stakeholder, "*energy costs will be different after the COVID-19 pandemic and up to 2030, affecting the financial viability of investments*" (**POL**).

RQ84. What are the possible environmental and economic effects of unforeseen events with high social impacts (e.g., COVID-19 pandemic) to the energy system and how can they be mitigated?

RQ85. "What is the impact of COVID-19 on the RES and EE targets for 2030 due to changes in income, consumption levels, and effect on economy and how could this impact be mitigated (e.g., via public funded mechanisms such as "Exoikonomo- Aftonomo")" (POL)?

3.2. Regional level case study: “The Nordic Region- a frontrunner of the decarbonised energy systems”

In recent years, the institutional cooperation between five Nordic countries (Denmark, Finland, Iceland, Norway, and Sweden) in the climate and energy field accelerated substantially. In 2015, the Nordic Council of Ministers[9] decided to strengthen it, review the activities undertaken so far and decide about strategic directions of cooperation for the decades to come (Ollila, 2017). In 2016, as a collaborative endeavour, the International Energy Agency (IEA), Nordic research institutions and the Nordic Energy Research Council (NERC)[10], an intergovernmental organisation under the Nordic Council of Ministers, published the “Nordic Energy Technology Perspectives” (NETP), a report looking at regional long-term, cost-efficient, and low-carbon technology pathways that provide scientific insights on how to go towards a carbon-neutral energy system, compatible with the Paris Agreement (Norden & IEA, 2016).

At the beginning of 2019, this scientific exercise has been backed politically by Nordic Prime Ministers, which declared a Nordic Carbon Neutrality (Nordic Co-operation, 2019). In this context, later that year, the Nordic Energy Research released a report that tracks the Nordic progress towards a carbon neutral society by 2050, highlighting trendsetting technological solutions, while keeping in mind the social coherence within this process (Nordic Energy Research, 2019). In April 2020, an updated version of this report was published (Nordic Energy Research, 2020).

These reports present a bigger picture of the Nordic clean energy pathway, place the region as a European leader of the sustainable transition, and describe various drivers required to achieve a carbon neutral system (Nordic Energy Research, 2019, 2020). These drivers are: **(i). Transforming the power sector**, **(ii). Boosting bioenergy**, **(iii). Electrification of transport**, **(iv). Electrification of heat supply**, **(v). Decarbonisation of industry**, **(vi). Energy efficient & smart buildings**, **(vii). Green mobility**, and **(viii). Energy storage & CCS**. These drivers constitute the directions and technological priorities of the Nordic countries for the years to come, and they should serve as an opportunity for business and innovation, and secure a socially and environmentally sustainable energy transition (Nordic Energy Research, 2019, 2020).

However, while the 2019 and 2020 “Tracking Nordic Clean Energy Progress” reports holistically present the advancement of the Nordic pathway to carbon neutrality, it is not clear whether they reflect and answer concerns, needs, and demands of stakeholders interested in the future Nordic energy system. This section relies on these reports in order to create a basis for identification of critical issues and challenges for the joint energy transition of the Nordic countries. It proposes six different thematic areas related to the decarbonisation of Nordic economies, which are a starting point for a further discussion aiming at opening a black box of potential requirements of stakeholders and modelers dealing with future energy systems.

3.2.1. Background on Policies & Targets

Nordic countries aim at becoming carbon neutral and leaders in the fight against global warming (Nordic Co-operation, 2019). The joint political declaration proves the commitment of the five states towards carbon neutrality, thus, contributing to limiting the increase in the global average temperature to 1.5°C (Nordic et al., 2020). The NETP 2016 is the most relevant report targeting the Nordic region as a whole and providing a case study on how to go beyond the 2°C target, towards a carbon neutral energy system (Norden & IEA, 2016). NETP 2016 analysis is based on the “Carbon Neutral Scenario” (CNS), in which Nordic energy-related CO_2 emissions fall at least 85% by 2050. However, offsets are needed for the remaining 15%, thus, the CO_2

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[9] https://www.norden.org/en/nordic-council-ministers

[10] https://www.nordicenergy.org/

reduction pathway of this scenario should be regarded as a minimum requirement (Norden & IEA, 2016). Four key action areas for providing policy recommendations for Nordic countries are highlighted in the NETP 2016 (Norden & IEA, 2016):

- Reinforcing incentivisation for investments in flexible technologies and services (e.g., energy storage, demand-response, etc.),
- Enhancing Nordic and European cooperation regarding the grid infrastructure and electricity markets,
- Ensuring competitiveness of industry throughout the energy transition,
- Acceleration of decarbonisation of transport.

Also, three macro-level strategic actions have been set (Norden & IEA, 2016):

- Planning for a more distributed, interconnected, and flexible electricity system,
- Advancing the decarbonisation of long-distance transport and industry via ramping up technology development,
- Strengthening national decarbonisation and EE initiatives in transport and buildings.

As members of the EU, Denmark, Finland, and Sweden have in their NECPs strategies aligned with the five dimensions of the Energy Union, which aim at: **(i) decarbonisation in terms of both GHG emissions and removals and renewable energy**, **improving (ii) energy efficiency** and **(iii) energy security**, and **enhancing (iv) the internal energy market** and **(v) research, innovation, and competitiveness**. Since, Norway and Iceland are not EU members, they have not prepared their NECPs, and, thus, their strategic policy document are not structured around exactly these dimensions. However, both countries are aligned with the binding Effort Sharing reduction target to meet the commitments of the Paris Agreement. The targets of each country for GHG emissions reduction and renewable energy (only applicable for Denmark, Finland, and Sweden) are presented in **Table 6**.

Table 6. Summary of the national energy targets for each one of the Nordic countries towards 2030 and 2050

Country	GHG emissions reduction target	Renewable energy target
Denmark (Danish Ministry of Climate, Energy and Utilities, 2019)	Reduction of GHG emissions by **70%** in **2030** compared to 1990, working towards **net zero** emissions by **2050** at the latest	Share of approximately **55%** by **2030**; RES share in electricity above **100%** of consumption; **phasing out** coal in electricity production until **2030**
Finland (Ministry of Economic Affairs and Employment, 2019)	Reduction of GHG emissions by **39%** until **2030** compared to 2005 levels, achievement of **carbon neutrality** by **2035**	**51%** share of the gross final energy consumption until **2030**
Sweden (The Ministry of Infrastructure, 2020)	Cutting **net GHG** to zero by **2045** and then achieve **negative emissions,** reducing the emissions from activities on Swedish territory to **15%** of their 1990 levels	**50%** of final consumption of energy in **2020**; **100%** renewable electricity generation in **2040**
Norway (Norwegian Ministry of Climate and Environment, 2019) (Norwegian Ministry of Climate and Environment, 2020)	At least **50%** and towards **55%** reduction of GHG emissions **by 2030** compared with 1990, **80-95%** reduction of GHG emissions compared to 1990 by **2050**	N/A
Iceland (Government of Iceland. Ministry for the Environment and the Natural Resources, 2021)	**55%** reduction in GHG emissions by **2030** compared to 2005 levels, acting jointly with European Union, Member States and Norway to achieve this target	N/A

3.2.2. Energy Scenarios & Narratives

Reference Scenario- Carbon Neutral Scenario "CNS" (2020- 2050)

When looking at the generation mix in the Nordic countries, electricity generation from RES (i.e., hydro, wind, PV, and biomass) increasingly dominates the scene and provides 73% and 87.5% of electricity generation in 2030 and 2050, respectively. Hydropower will continue to play an important role in the system with a capacity of ca. 52 GW in 2030 and ca. 55 GW in 2050, covering around 50% and 55% of total electricity generation in 2030 and 2050. Variable RES (VRES, i.e., wind and PV) cover 17.3% and 30% of total electricity generation in 2030 and 2050. The relatively low share of VRES in the Nordic countries is due to the very large input from hydropower and the contribution from nuclear power stations in Finland. However, the amount of wind power grows rapidly and reaches 28.7 GW (25.3 GW onshore and 3.4 GW offshore) capacity in 2030 and 47.8 GW (44.4 GW onshore and 3.4 GW offshore) capacity by 2050. Electricity generation from solar PV could reach 4 GW capacity by 2030, remaining almost the same by 2050 (Norden & IEA, 2016). Biomass covers 7% and 5% of total electricity generation in 2030 and 2050 with a capacity of ca. 8 GW in 2030 and ca. 5 GW in 2050. The remaining electricity generation in 2030 and 2050 consists of 3% and 5% natural gas electricity generation with a capacity of ca. 9 GW in 2030 and ca. 13 GW in 2050, 2 GW of those being natural gas with Carbon Capture and Storage (CCS), and 20% and 6% nuclear electricity generation with a capacity of ca. 12 GW in 2030 and ca. 3 GW in 2050. A substantial and accelerated increase in transmission capacity by around 5 GW before 2030 and cross-border power exchange takes place. New interconnectors are developed both within Nordic countries and between the European continent and the Nordics. In 2030 the expected electricity supply will be ca. 440 TWh, while in 2050 the expected electricity supply will be ca. 427 TWh.

RES generators supply electricity under different RES business models (e.g., FiP contract, participation in the wholesale market, etc.). Aggregators serve as representation entities for RES generation/ integration. Electricity storage systems will include pumped hydro, compressed air energy systems (CAES), batteries, etc. Multiple electricity storage systems are grouped into virtual power plants and provide the missing power in cases where RES generation is low and demand is high (service to aggregators), or when voltage deviations occur (service to TSOs). Provision of chemical storage through biofuels, hydrogen production using electrolysers, and heat storage in district heating systems are also envisioned. Demand-side flexibility potential in industry (e.g., load shifting, peak shaving, fuel shifts, etc.) is between 5,000 and 6,000 MW, and between 4,000 and 7,000 MW in households in the Nordic region. Of the total potential, 4.2 GW in 2030 and 5.7 GW in 2050 are related to nominal electricity demand (for example, within the industry sector) and a further 4.5 GW in 2030 and 5.8 GW in 2050 are related to electrical heating (direct heating as well as heat pumps in buildings). Moreover, a potential for flexible charging of EVs is included, which grows from 0.5 GW in 2030 to 1.5 GW in 2050.

On the demand side, improving EE is a key priority. Deep energy renovations with renovation rates between 2% and 3% per year are needed across the Nordic countries until 2050. Total energy used in the Nordic buildings sector decreases to roughly 1 EJ (27% below 2013 levels) in 2050, with space heating demand decreasing to 440 PJ in 2050 (45% reduction), because of rigorous EE improvements across the Nordic building stock. Total electricity (49.4% of final energy supply) and district heating (36.1% of final energy supply) consumption accounts for 85.5% of buildings sector final energy demand in 2050, while coal, oil, and natural gas consumption go to zero by 2050. Total biomass consumption decreases (5.4% of final energy supply). By contrast, heat pumps and solar thermal collectors grow considerably (9% of final energy supply), replacing the vast majority of oil, gas boilers and direct electric resistance heating. In the transport sector, fuel shifts are also substantial, as fossil fuels give way to biofuels and electricity, which collectively represent three-quarters of overall transport energy use in 2050. By 2050, biofuels comprise nearly two-thirds (63%) of the total final energy use in transport, with Sweden accounting for more than one-third (36%) of this consumption. Fossil fuels account for only 25% of final energy use in transport and electricity for 10%. Digitalisation in the transport sector reveals new business models (e.g., V2G, etc.), in which car batteries serve as an energy resource when the vehicle is stationary. With regards to the industrial sector, electricity continues to be the most consumed energy vector (46%) of the Nordic final industrial energy demand by 2050, followed by biomass and waste (26.1%). Oil (12.8%), natural gas (7.4%), coal (4.2%), and commercial heat (3.5%) cover the remaining industrial energy demand. CCS provides an alternative that can significantly reduce direct CO_2 emissions from industrial processes. Cumulatively, 93 $MtCO_2$ are captured and stored in the period 2020- 2050 in Nordic countries.

Achieving a near-zero emission Nordic energy system by 2050 entails at least 85% reduction in emissions by 2050 (from 1990 levels). The respective reduction in emissions by 2030 will be around half of the total GHG reduction target of 2050 (41- 44%). Total GHG emissions will be 119.8 $MtCO_2eq$ in 2030 and 30.6 $MtCO_2eq$ in 2050. Key specifications and targets of the case study at a regional level are summarised in **Table 7**, while direct energy-related CO2 emissions, based on the "CNS" by sector and country, are presented in **Table 8**. Note that the share of direct emissions from industry and transport increases as total emissions fall in the "CNS", underscoring the challenges that remain in these end-use sectors.

Table 7. Key specifications and targets of the Nordic case study at a regional level

Scenario	CNS (2020- 2030)	CNS (2030- 2050)
Total GHG emissions reduction targets	Around **half** of the total GHG reduction target of **2050** should be met in **2030** **(41- 44%)**	at least **-85%** relative to 1990 levels
Total GHG emissions (Mt CO_{2eq})	119.8	30.6
RES target	**73%** RES in total electricity generation	**87.5%** RES in total electricity generation

Table 8. Nordic direct energy-related CO_2 emissions, according to the "Carbon Neutral Scenario", by sector and by country, and at a regional level. Source: (Norden & IEA, 2016).

Mt CO_2	Denmark			Finland			Iceland			Norway			Sweden			Nordic Region		
	2013	**2030**	**2050**	**2013**	**2030**	**2050**	2013	**2030**	**2050**	2013	**2030**	**2050**	2013	**2030**	**2050**	**2013**	**2030**	**2050**
Power generation	16.9	3.8	0	22.2	11.6	0	0	0	0	2	1.7	0	7.2	2.2	0	48.3	19.3	0
Other transform.	2.1	0.2	0	2.4	2.7	0	0	0	0	10.4	3.8	0	1.7	0	0	16.6	6.7	0
Industry	4.2	2.7	1.6	10.4	7.7	3.2	2	1.3	0.4	8.4	9	4.7	12.5	7.6	3.5	37.5	28.3	13.4
Transport	15.7	11.2	2.6	14.2	10.7	2.7	1.4	1.4	0.2	16.5	12.1	2.3	27.1	22.6	5	74.9	58	12.8
Buildings	3.2	0.6	0	2.2	0.9	0	0	0	0	1	0.3	0	1.3	0.1	0	7.7	1.9	0
Other	1.8	1,5	0.9	2.1	1.2	0.9	0.7	0.7	0.7	2.1	1.9	1.7	0.4	0.3	0.2	7.1	5.6	4.4
Total	**43.9**	**20**	**5.1**	**53.5**	**34.8**	**6.8**	**4.1**	**3.4**	**1.3**	**40.4**	**28.8**	**8.7**	**50.2**	**32.8**	**8.7**	**192.1**	**119.8**	**30.6**

3.2.3. Critical issues, Challenges & Research questions

In this analysis, we follow a similar approach to the one presented in the National level case study, however, adjusted to the objectives of this study and combined with the specificities of the energy models applied in SENTINEL. First, we structure the challenges of the future Nordic energy system around six priority areas as presented in **Table 9**. This choice has been determined by both literature findings and stakeholders' insights as well as through discussions with SENTINEL modellers.

Table 9. Six thematic priority areas applied in the Regional level case study.

1. **Transforming the power sector**
2. **Sector coupling: implementing smart energy systems & P2X solutions**
3. **Decarbonisation of industry & Carbon Capture and Storage**
4. **Energy efficiency & smart buildings**
5. **Environmental aspects & implications**
6. **Socioeconomic aspects & implications**

Second, in order to identify contextual critical issues and challenges related to these priority areas, we combine the evaluation approach of the Nordic Energy Research with the theoretical underpinnings presented by the *Three types of knowledge tool*. Next sections shortly summarise each of the thematic areas and propose specific research questions, which could frame further modelling exercises. This framing is based either on the insights stemming from the literature, or on the findings of the interaction with stakeholders at the online workshop. Because of a different character of this event, compared to interviews run in the National level case study, we do not present a defined stakeholder group, which a given quotation comes from.

3.2.3.1. Transforming the power sector

The Nordic power sector is already close to being decarbonised and holds promising prospects for the integration of more wind power and a role as an electricity hub for the rest of Europe: including electricity export as well as balancing European VRES. This creates a situation, in which the effort to fully decarbonise the power sector is relatively small, compared to the rest of Europe. *"However, transforming the Nordic power sector requires better governance and more institutional cooperation between the countries, which, despite the joint Nordic Carbon Neutrality Declaration* (Nordic Co-operation, 2019), *currently seems to be insufficient*."

Electricity generation & balancing

Where we are

The electricity market is currently experiencing an excess of generation capacity, leading to historically low electricity prices. Low electricity prices can lead to lower returns on investment in traditional baseload capacity like thermal and nuclear production (Ollila, 2017), and, thus, the elimination of certain types of generation units, which are necessary when demand peaks (Sovacool, Kester, de Rubens, & Noel, 2018). The flexibility of the traditional Nordic power market may be challenged by the following factors: **(i)** growth in intermittent generation, **(ii)** less flexible thermal generation, and **(iii)** surplus generation in years with normal precipitation (Spodniak, Ollikka, & Honkapuro, 2021).

Where we want to get to

Electricity generation from wind power is expected to displace production from fossil and nuclear plants. The CNS assumes 30% of electricity generation from wind power in 2050 (in comparison to 7% in 2013) (Norden & IEA, 2016). Regarding the potential of solar power, stakeholders mentioned that "*there is a dominating perception that solar power use could result in stranded assets across other technologies*."

RQ1. How much wind and solar VRES generation is needed in 2030 and 2050 in the Nordic region to meet demand requirements (e.g., electrification) of other sectors? What is the potential of bioenergy deployment in terms of power generation?

How to get there

The large hydro reservoirs and plants in the Nordic region are capable of balancing and storing VRES generation in continental Europe and UK. Currently, there has been a lot of flexibility in the Nordic power system and the region could probably serve as provider of flexibility without upgrade of its pumping capacity (Graabak & Korpås, 2016). According to stakeholders, the potential of water reservoirs in the Nordic Region to balance VRES is limited: "*Hydro reservoirs might not be the panacea of dispatchable energy. As their limited capacity and their dispatchability is highly weather-dependent, changing weather conditions related to climate change could exacerbate these issues*."

RQ2. In case that VRES units are not dispatchable, can conventional generating resources, such as hydro plants, and the imported electricity meet the residual demand when large RES penetration occurs?

RQ3. What should be the hydropower capacity in the context of balancing renewables? How will this capacity change due to changing weather conditions resulting from climate change? How much pumping capacity will be cost-optimal regarding the future Nordic hydropower production?

RQ4. How much flexible generation capacity is needed in 2050 to meet demand requirements with an aim to maximise RES penetration?

The volatility of renewable electricity production can be balanced also by international electricity trade (Pursiheimo, Holttinen, & Koljonen, 2017).

RQ5. In case of VRES overcapacity, what is the contribution of electricity exports in the supply/ demand equilibrium, both in the case of the existing storage capacity and of an increased storage capacity scenario?

Except of growing renewables, it should not be forgotten that in the Nordic countries nuclear power still plays an important role. "*Nuclear power cannot be assumed to be out of the picture. Although it is economically unfavourable, there is no strict target for its removal, and in Finland there are even plans to commission new nuclear block(s)*." In contrast to this argument, Pursiheimo et al. (2017) mention that the path to a renewable energy system is costly and requires high investments, notably in Finland and Sweden, with phased-out nuclear power (Pursiheimo et al., 2017).

RQ6. Will nuclear energy be considered as a contributor to a future energy system in the Nordic Region? Will there be new nuclear power plants commissioned? What will be the contribution of power generation coming from nuclear energy in the electricity mix by 2050?

Distributed generation, storage & curtailment

Where we want to get to

70% of the total wind capacity is projected to be installed in Denmark, with two-thirds of the total wind capacity being onshore, highlighting the need for proper siting and public approval (Sovacool et al., 2018).

RQ7. What should be the geographical siting of onshore and offshore wind projects used to replace conventional power in terms of minimising system losses and costly network upgrades? How can their geographical siting be optimised in terms of land requirements?

The Nordic power system is highly based on hydropower (57% of the electricity mix in 2018). Therefore, there has not been a regular need for curtailment of wind generation. However, the rapid increase of wind power capacity means that regular curtailment may be necessary in the future (Nycander, Söder, Olauson, & Eriksson, 2020).

RQ8. What is the maximum wind penetration that could be accommodated within the Nordic electricity system with acceptable levels of curtailment? How much VRES capacity and storage is

needed to reach a 100% renewable energy electricity mix in the Nordic region without excessive curtailment?

How to get there

Achieving the transformation of the power sector will require investments from the private sector, which should be initiated by incentives.

RQ9. How will the added RES capacity affect the cost of emissions and the system marginal price? What is the necessary total investment cost for the added RES capacity and what is the total system cost?

RQ10. What types (e.g., tax credits, etc.) and levels of incentives could facilitate the deployment of onshore and offshore wind energy? What should be the levels of investments for the transformation of the power sector?

Furthermore, capacity mechanisms can be another way to incentivise investors. These mechanisms can take different forms. Payments can be made either in return for maintaining existing capacity or for investing in new capacity. Capacity can also be provided from the demand side, e.g., if a large consumer postpones their usual electricity demand (Ollila, 2017).

RQ11. Should generators be paid just for the electricity they supply, or should they also receive capacity payments?

Alternative business models could have different impact on RES penetration.

RQ12. What are the expected RES adoption rates under different business models? Do novel business models (i.e., leasing, sale and lease back) attract risk-averse consumers' investment interest?

Prosumers might play an important role in the increase of the shares of RES electricity.

RQ13. What business models could increase chances of prosumers investing in RES projects?

RQ14. How do different RES/storage business models (i.e., P2P, P2G and OPG) perform in terms of profit for different actors? What are the respective governmental costs, if any?

The technical management of VRES intermittency is a significant challenge for the Nordic countries, which have not abundant hydropower, in contrast to Norway and Iceland, and have also a plentiful supply of wind energy (e.g., Denmark) (Sovacool et al., 2018). Electricity generation from VRES is largely fluctuating, and, thus, should be balanced, as well as it is actually replacing some of the backup power plants, providing ancillary services and balancing. Consequently, energy storage could facilitate integrating this amount of renewable energy (Sovacool et al., 2018). Electricity production from VRES might also require utilisation of the storage options that already exist in the interconnected system or even more, depending on the options.

RQ15. What is the optimal onshore/ offshore wind capacity ratio to achieve maximum wind penetration with low curtailment with and without storage technologies? What would be the power storage needs considering the reserve capacity requirements in the interconnected Nordic power system?

Interconnections

Where we are

The Nordic power system (apart from the isolated system of Iceland) is already heavily interconnected.

Where we want to get to

Shifting to larger electricity imports is an increasingly important question regarding security of supply (Sovacool et al., 2018).

RQ16. What would be the contribution of interconnections to the operation of the Nordic power system? Can continental interconnections be used to balance the fluctuations of RES due to weather changes?

How to get there

Strengthening interconnections with the central European electricity system may be needed, potentially affecting electricity markets in the Nordic countries (Bolwig et al., 2020).

RQ17. What possible new interconnections should be considered? What options exist for Iceland connecting to the rest of the Nordic region (e.g., high-voltage direct current (HVDC) connection, production and shipment of synthetic fuels, etc.)?

Transmission and distribution

Where we want to get to

Moreover, more decentralised electricity production will require development of transmission and distribution capacities. Rising electricity generation would change the power system from the current highly centralised grid development and management to a transmission and distribution system with load balancing at a local scale (Tenggren, Wangel, Nilsson, & Nykvist, 2016). "*Decommissioning conventional power plants in favour of wind power will require electricity transmission line reinforcement. Without transmission line reinforcement, there is a risk that it will not be possible to share higher levels of wind generation across all Nordic countries*."

RQ18. What will be the requirements regarding transmission lines to guarantee a stable electricity supply from wind power generation units to consumption centres? Can offshore wind farms be used to strengthen interconnections among Nordic countries and EU?

How to get there

RQ19. Which actors will bear the costs of the development of transmission and distribution capacities? What incentives could be provided to them in order to pay for the transformation of the power system?

"*Storage will be essential to add flexibility to the system, however, it might be challenging for the implementation of hydrogen pipes, which actually could prove to be cheaper than new overhead electricity lines*."

RQ20. What would be the difference in cost between building hydrogen pipes and new overhead electricity transmission lines?

Transformation implications

Where we want to get to

A decarbonised power system can affect the local level. It will be necessary to maintain the reliability of local grids, especially pertaining to network upgrades and the local transmission and distribution of electricity. This challenge follows both the further integration of renewables and the expected effects of electric mobility on local grids, their demand and potential storage capacity and is exacerbated by the ownership and business model of local grids, where the DSOs often decide against full line development, and rather opt for maintenance and incremental localized upgrades (Sovacool et al., 2018).

RQ21. What will be the impacts of decarbonisation at the local level and what will be the requirements in terms of maintaining their reliability?

The transformation of the power sector in the Nordics requires a proper governance and coordination.

RQ22. Will an increased offshore generation in the North Sea (where Sweden and Finland have little access to) create/ exacerbate issues with spatial disparity?

"*High levels of industrialisation in the Nordics create additional challenges for the power sector's transformation. There are industries which cannot operate in certain areas due to lack of power. Increasing electrification of the whole energy system could further threaten industries, stemming from unstable electricity supply. Moreover, cross-sectoral electrification, involving the transportation and heating sectors, again raises the issue of who will pay for this transformation*."

RQ23. Will the transformation of power sector keep pace with cross-sectoral electrification? Will the RES-based electricity production help to quickly decarbonise other sectors?

RQ24. How much electricity production will be needed to produce enough hydrogen to decarbonise the industry? At which point in time will this production be fully based on renewables?

3.2.3.2. Sector coupling: implementing smart energy systems & P2X solutions

During the discussion with stakeholders, it was mentioned that: "*the electrification of transport and heat supply is important to switch both sectors to renewables*."

Decarbonisation of heating

Where we are

Integrating heat pumps and electric boilers into heating networks adds flexibility to the power and heat system. In Denmark, there is a need to start converting district heating to electricity from heat pumps, but this process is very slow due to high electricity taxes (Sovacool et al., 2018). With well-established district heating grids in the Nordic countries, the implementation of P2X solutions makes sector coupling more complex to model.

Where we want to get to

Regarding the heating sector, there is a demand to electrify the heating supply in both individual heating households and the well-developed district heating grids. This can go hand-in-hand with EE measures and expansion of low temperature district heating. Adding a large capacity of heat pumps to district heating networks may affect the whole electricity market, as, due to marginal pricing in the Nordic electricity market, the electricity price increases with each increase in total load (Helin, Syri, & Zakeri, 2018).

RQ25. What should be the contribution of different heating methods (e.g., heat pumps, waste heat, and heat storage) to these grids to achieve efficient district heating?

How to get there

To increase electrification of the heating sector and harvest all the benefits of smart energy systems, district heating systems must change. "*Heat pumps, waste heat, and thermal storage needs to be implemented in the district heating grids to accommodate for smart energy systems. Heat pumps and heat storage can provide additional flexibility cost-efficiently, being effective solutions to integrate VRES. Nevertheless, heat pumps might not be suited for quick ramping, so other options could be better to provide flexibility when handling excess electricity production. This technology can, however, be used as efficient heating solutions in areas with no district heating, or where it is not feasible, especially since other not very efficient technologies, like direct electric heating and air-to-air heat pumps, are still in use*."

RQ26. In which areas without district heating, would it be more cost-effective to implement heat pump projects and in which to develop complete district heating systems? What should be the timing of replacing inefficient direct electric heating with heat pumps?

RQ27. How would the increase of electrification of heating impact the electricity mix? What are the reserve needs, and how to potentially deal with increased peak electricity demands?
RQ28. To what extent can heat pumps and thermal storage provide additional flexibility to the electricity system in a cost-efficient way?
RQ29. How is the life-cycle cost of heat pumps affected when services (i.e., load shifting) are offered to the grid?
RQ30. What GHG emission reductions could result from the adoption of heat pumps in the heating sector, and what would be the macroeconomic repercussions?

The electrification of heating can have consequences for the power grid.
RQ31. What services could different flexibility sources, like batteries, data centers, hydrogen production, and heat storage, provide to the grid?

Decarbonisation of transport

Where we are
The implementation of smart renewable energy systems in the transport sector is a major challenge with potential for system flexibility. The transport sector poses the greatest challenge when it comes to further decarbonisation of the Nordic energy system. Substantial achievements have been made in the deployment of electric vehicles in Norway and biofuels in Sweden and Finland. Nevertheless, the transport sector still accounted for some 45% of all energy-related CO_2 emissions in 2016 (Nordic Energy Research, 2019). Regional cooperation is considered very important for this transition, since it is hard to align efforts on greening the transport sector within one country– but much more difficult at regional level (Ollila, 2017).

Where we want to get to
Nordic countries assume to phase-out the conventional internal combustion engines vehicles by 2050, whereas battery EVs should constitute 60% of all vehicles in the Nordic countries (Nordic Energy Research, 2020). This also emphasises the need for power to gas and/ or alternative fuel solutions. The need for clean fuels in transport may cause increased demand for liquid biofuels, hence, affecting biomass prices and altering fuel usage for heat and electricity generation (Mustapha, Kirkerud, Bolkesjø, & Trømborg, 2019). As stated, also, by the stakeholders: "*Electric vehicles and P2X infrastructure have to be implemented to fit both passenger transport and heavy transport needs, as well as demands in power plants and industry. Passenger transport can rely on biofuels as a short-term solution, which should be replaced by electrification in the long term. This, however, can trigger a challenge of resource constraints in the biomass supply, when looking at the use of biofuels not only as an alternative fuel for transport, but also for covering power plants and industrial demands*."
RQ32. What is the necessary P2X infrastructure and how much biomass will be needed for production of biofuels? What will be its contribution to covering energy demand (e.g., power plants and industrial demand needs, etc.)?
RQ33. How will an increased production of biofuels affect the use of biomass for heat and electricity generation? How will electricity prices and investments in generation capacities be influenced by biofuel production and carbon emissions costs?

How to get there
The electrification of transport and implementation of P2X would require rapid investments in vehicles and infrastructure. This infrastructure has to be implemented to fit both passenger and heavy transport needs, as well as demands in power plants and industry.

RQ34. What should be the levels of investments in EVs and P2X technologies in the transport sector between different Nordic countries?

RQ35. To what extent can e-roads be considered as a solution? In which areas should they be implemented? Should they be considered mostly for the long haul?

An electrified transport will have impact on the operation of the power grid but could also provide opportunities for provision of services to the grid. "*System integration will help in lowering the strain on the electricity grid coming from an increased transport demand supplied by electricity*."

RQ36. What are the additional electricity consumption patterns resulting from the electrification of the transport sector? What would be the change in energy consumption after a certain incorporation of electric vehicles?

RQ37. How would the electrification of the transport sector affect the electricity mix and electricity prices? Are there increased needs for reserves and what is the role of imports due to the increased peak demand?

RQ38. What policy mechanisms (e.g., subsidies, tax exemptions, etc.) can further accelerate the transition of electric mobility? What non-financial incentives (e.g., free parking/ charging, access to bus lanes, toll road exemption, etc.) can incentivise consumers (Kester, Noel, Zarazua de Rubens, & Sovacool, 2018a)**?**

Regarding V2G, the challenges concern technological (i.e., communication complexity and battery degradation), regulatory (i.e., dynamic price mechanisms, bidding and aggregation), market (i.e., costs and competition from other flexible storage technologies), and end-user-related (i.e., consumer acceptance) factors. Such technologies need to be adjusted so that they can facilitate aggregated short-term storage markets (Kester, Noel, Zarazua de Rubens, & Sovacool, 2018b).

RQ39. What policy mechanisms (e.g., net metering, adapted tax regimes, etc.) can speed up the transition towards V2G technologies? What will be the role and legal position of aggregators who 'aggregate the EVs and then trade the energy?'

RQ40. What is the total system cost of EVs affected when services (i.e., load shifting and covering of household needs with car battery) are offered to the grid?

RQ41. With regards to vehicle storage, V2G and G2V business models could be an option for investors? What is the optimal combination of V2G and G2V models so that load 'peaks' and 'valleys' are smoothened effectively? What other effects could V2G and G2V cause to the electricity system? Could smart-charging contribute to peak shaving?

RQ42. What levels of RES penetration could be achieved using the V2G business model in the residential and transport sectors?

RQ43. How much (vehicle/ stationary) storage is needed to achieve 100% RES absorption (with minimum curtailment) within each electricity system of the Nordic region when the transport sector is fully electrified? What is the maximum peak shaving that can be achieved with the use of different types of storage (i.e., vehicle/ stationary)?

Public fast recharging infrastructure is considered as a primary need for consumers. Additionally, private, or semi-public charging at home, work or apartments is also deemed necessary. Building and zoning regulations could be set for implementing charging facilities in private, commercial, and shared housing buildings (Kester et al., 2018a).

RQ44. How many charging points and in what distance from each other should be provided to fully cover the demand of such EV fleet? What would be the cost of the required infrastructure?

RQ45. What should be an optimal charging speed of the charging points? What should be an optimal number of simultaneous connections at the charging points?

Maritime/ Heavy Goods Vehicles transport

How to get there

"*Heavy goods vehicles (HGV) and maritime transport can rely on P2X solutions, such as synthetic fuels or H_2, instead of being fully electrified, whereas synthetic fuels could serve as 1-to-1 replacements to current fuels and H_2 could be produced via electrolysis using fluctuating renewables*."

RQ46. What are the requirements for e-fuels and P2X technologies for maritime and aviation transport?

RQ47. "*If full electrification is followed, what is the potential of batteries for the decarbonisation of HGV with respect to their technical requirements (i.e., weight, cargo and autonomy)*?"

3.2.3.3. Decarbonisation of industry & Carbon Capture and Storage

"*Challenges related to the decarbonisation of industry encompass issues like economic consequences and competitiveness; resources and environmental trade-offs; societal concerns and public acceptance; or the technology incorporation*."

Decarbonisation of industry

Where we want to get to

Nordic total final industrial energy consumption is reduced by 9% in the CNS by 2050 compared with 2013 levels for similar industrial activity (Norden & IEA, 2016). Based on stakeholders' feedback: "*there is potential to develop energy technologies using waste, but here, a further development of this direction depends a lot on the EU legislation for negative emissions and limits or caps for air pollutant emissions from small and medium waste fueled combustion sources*."

RQ48. What should be the level of contributions of various fuels and feedstocks (i.e., coal, oil, natural gas, biomass and waste, electricity, and heat) that would allow for such reduction? What could be the contribution of waste with regards to the reduction of industrial GHG emissions? Which type of biomass is the most energy- and cost-efficient to be used in industrial processes?

RQ49. What are the possible energy savings due to process improvements and transformations in the industrial sector?

How to get there

As described in the "Energy Technology Perspectives ETP 2020" (IEA, 2020) the existing infrastructure, with a relatively long lifetime in heavy industry could be a barrier to the sector's decarbonisation. Moreover, the required investment in the industry sector should be quantified, and technical difficulties for the alternative options should be examined.

RQ50. How is the technology adoption of new assets influenced by the assumed average lifetimes of previously installed equipment in the industry sector?

RQ51. Which industrial sectors in specific Nordic countries shall be prioritised in the context of industrial emissions' reduction? How should the industrial units be managed in terms of short- and long-term balancing of the CO_2 emissions?

Carbon Capture and Storage

Where we want to get to

While the Nordic industrial sector is already energy- and material efficient, further improvements will require technological innovation, including substantial application of carbon capture utilisation and storage (CCUS). In the CNS, CCS is expected to contribute to the decarbonisation of industrial sectors, where fossil fuel reduction seems to be particularly challenging by 2025 (Nordic Energy Research, 2020). This also relates to the electrification of heavy industry and the fact that industrial energy users can also become energy producers.

RQ52. Is CCS a cost-effective option to be considered as a GHG emissions mitigation strategy in the industrial sector? What are the annual rates of CO_2 capture to decarbonise the Nordic industry? What is the potential of carbon capture and mineralisation (CCM) units in the Nordic Region?

How to get there

"*Norway already would need to capture 7 million tons of CO_2/ year to allow for 85% of emissions reduction from the industrial sector by 2050, what are the available capacities for CCS? Second, how would it be achieved: by the use of pipelines or ships? Third, how much would such solution cost? The Norwegian CCS business model could be followed by the rest of Europe*." Comparing cost for ship and pipeline transport as a function of volume and distance shows that ship transport is the least costly transport option not only for most of the sources in the region individually but also for most of the potential CCS clusters (Kjärstad, Skagestad, Eldrup, & Johnsson, 2016).

RQ53. Which policies could encourage the adoption of CCS systems with high carbon capture rates? Where and how many CCS units shall be implemented to allow for such emissions reduction?

RQ54. What CO_2 transport infrastructure would be required and what storage capacities would be necessary? What would be the costs of the CO_2 transport to CCS units by pipeline and by ship?

Hydrogen

How to get there

"*The use of hydrogen can enable the decarbonisation of industries*."

RQ55. Which mechanisms could promote investments in hydrogen technologies in the industrial sector? How will the investments in CCS influence the investments in hydrogen technologies?

RQ56. How much hydrogen will be needed for direct reduction of raw materials in industrial production (e.g., iron in steel production, etc.) and balance onshore and offshore wind units? Which locations are most suitable for electrolysers facilities in the Nordics?

3.2.3.4. Energy efficiency & smart buildings

Energy efficiency

Where we are

Since Nordic urban areas are expected to grow at twice the rate of previous decades, measures to improve EE of the buildings will become particularly important. "*Considering the population growth in Nordic cities, the demand to refurbish existing buildings should increase at a quicker pace. While the new building policies in Nordic countries are strong, energy consumption remains high in the region, because existing buildings are not of the same high standard. Furthermore, since the electricity prices are low (e.g., in Sweden), the present incentives aimed at reducing electricity demand are insufficient. Also, due to cultural habits, like for instance in Sweden, where people like to overheat their homes in winter, energy consumption per building is still relatively high*."

Where we want to get to

Energy demand in the Nordic region has been decreasing in the last decade, indicating an optimistic trend. As the CNS assumes, the energy consumption of the building sector will decrease by 27% in 2050 compared with 2013 levels (Nordic Energy Research, 2020).

RQ57. What would be the energy demand of the building sector in Nordic countries by 2050, if no further actions/ policies are taken?

RQ58. What is the potential of PV panels installed on the rooftops to contribute to generation of energy consumed in the building sector?
RQ59. What should be the maximum levelized cost of saved energy of the main household appliances with the best efficiency labels to guarantee the energy consumption reduction?

How to get there

EE options can work together with RES installations at a building level. In this context, "*the measures, which could provide substantial energy savings encompass energy-efficient water heating systems and heat pumps should continue to replace existing (direct electricity) heating systems*."
RQ60. What are the optimal energy efficiency and PV investments in buildings to achieve cost effective synergies between RES and demand in the building sector? What are the rebound effects due to behavioural consumption patterns?
RQ61. What is the overall potential of energy savings by changing the setpoint of the indoor heating systems or implementing energy efficient water heating systems?
RQ62. What kind of policies could promote the adoption of heat pumps (and other EE measures) by improving the economic viability of the technology (e.g., subsidies)?
RQ63. What adoption rates of heat pumps are expected in the residential sector under different business models (e.g., solar-assisted heat pumps, Energy Performance Contracts (EPCs) for heat pump installations, etc.)?

According to the stakeholders, "*there is a rather limited interest in defining high performance buildings in the region (at least in Sweden) like passive house or nearly-zero energy building (NZEB)*."
RQ64. How many new, passive or nearly-zero emission buildings shall be built due to the growing urban population in the Nordic countries? What should be the renovation rate and pace of the old building stock?

Smart buildings

How to get there

Smart buildings could work in collaboration with smart grids to support the operation of a flexible power system. "*Since electric vehicles' owners primarily charge their cars at home, there is a shift of electricity demand towards the residential sector. Charging patterns influence peak electricity demand and the demand profile overall*."
RQ65. To what extent could demand-response technologies limit the need for costly storage installations and increase the system's flexibility?
RQ66. What is the foreseen temporal peak demand of the residential sector, resulting from a switch to EVs and charging them at home?
RQ67. What are the benefits of combining electricity storage with demand-response technologies and how are these benefits distributed between actors in the electricity supply chain? What financial incentives should be applied to attract consumers' participation?

3.2.3.5. Environmental aspects & implications

Bioenergy

Where we want to get to

The CNS foresees that bioenergy will become the energy carrier with the largest share in 2050 with a supply of over 1600 PJ (Norden & IEA, 2016). About 16% of total Nordic biomass demand across all sectors will need to be met by imports in 2050, according to CNS (Nordic Energy Research, 2019). "*While biomass can* *be stored relatively easy, it is not particularly energy dense (compared to natural gas for example) and environmentally friendly, given the life-cycle of carbon emissions. Moreover, its use and access differ between the Nordic countries and not all of them are keen to sacrifice biodiversity to produce more bioenergy*." "*Regarding biomass related impacts, in some of the northern countries this resource is mostly imported, leading to transboundary issues*."

RQ68. How much biomass will be needed to produce the required bioenergy? How much new storage volume for biomass will be needed, if using bioenergy for local energy consumption?

Raw materials

Where we are

The application of technologies leading to a decarbonised energy system will result in domestic and externalised environmental impacts related to extraction of minerals and water and land use.

Where we want to get to

"*Realising the pathway to carbon neutrality will require significant amounts of raw materials to produce the equipment, infrastructure and vehicles*." The need for a large quantity of batteries results in dependency on mineral sources. The stakeholders shared their thoughts regarding the circular economy of recycling batteries after their life-cycle instead of disposing them, which will depend, for example, on the dominant types of batteries.

RQ69. Which battery types will be dominant? Should their re-usability and re-cyclability capacities and rates as well as their needs for raw materials play a role in that? Which batteries will be used for light and heavy transport vehicles depending on their tonnage?

RQ70. What is the most efficient and sustainable way to exploit batteries after their lifetime? What are the environmental benefits of exploiting the potential of batteries after their lifetime?

RQ71. What are the life-cycle impacts of different types of batteries considering their natural material usage and renewable material usage?

A similar situation is to be expected with renewable technologies. In this context, stakeholders agreed that potential supply restrictions of raw materials are the main risk for implementing renewable energy system technologies. This problem concerns in particular raw material inputs needed for EVs, PV, batteries, and wind turbines.

RQ72. Which technologies have the potential to achieve lower life-cycle impacts? What quantity of materials will be needed to cover new wind and solar power investments?

Trade-offs between nature protection and energy production

Where we want to get to

The way leading to carbon neutrality can create trade-offs between nature protection and energy production. Stakeholders agreed that the success of biomass as a heat and fuel source is dependent on land-use constraints and various environmental impacts.

RQ73. What will be the available land area for energy crops and renewables deployment based on current land use? What is the environmental impact of the land-use potential?

RQ74. What will be the biodiversity loss due to cultivating monocultures for energy crops and renewables deployment? What is the biodiversity loss due to extraction of raw materials needed for different renewable technologies and batteries?

RQ75. What are the water impacts due to cultivating energy crops and extraction of different raw materials, depending on the renewable technology?

RQ76. What are the environmental co-benefits and implications for air quality resulting from different technologies used for energy production?

Carbon leakage/ emissions

The spatial and temporal variations of marginal electricity generation will increase in the future. This combined with the electricity exchange in the EU may lead to possible emission leakage between EU countries (Olkkonen & Syri, 2016).

RQ77. What is the carbon leakage of different energy configurations? What would be the main geographical spots where such an environmental impact would be concentrated?

RQ78. How are the total emissions (by economic sector) expected to evolve in each country of the Nordic Region, when the centralised power system transforms into a system with increased participation of decentralised structures (e.g., energy communities, etc.)?

3.2.3.6. Socioeconomic aspects & implications

The recent decision at the EU level to increase the 2030 GHG reduction target brought even more importance to the need for creating an energy transition that is socially just and politically accepted. The Nordic Region's role as EU frontrunner raises issues of its responsibility and effort sharing, as well as aspects of socially and politically accepted energy planning and policy, including distribution of benefits and costs, design of policy instruments, public attitudes and acceptance, and job gains/ losses. However, according to stakeholders: "*not all political parties will express their support for effort sharing*."

Social acceptance issues

Where we are

The different local awareness and perceptions towards CCS on the community level should be seen in relation to the CCS policies of Nordic countries. As deployment of CCS ultimately will require an aggregation of acceptance in the socio-political, market and community dimensions, not only in one of the Nordic countries, but in all of them, political discussions between them will be needed. A joint statement of intention and/ or joint regional strategy for CCS infrastructure has already been suggested (Haug & Stigson, 2016).

Where we want to get to

To make Nordic emission targets realistically attainable, affordable technology for achieving negative CO_2 emissions will be necessary. One method to realise substantial negative CO_2 emissions is Bioenergy with Carbon Capture and Storage (BECCS). The Nordic countries constitute an excellent location for the development and deployment of this kind of technology. Finland, Sweden and Denmark are world-leading with respect to heat and power generation from sustainable biomass, while Norway is world-leading with respect to CCS (Rydén et al., 2017).

RQ79. Which renewable technologies are socially acceptable? Are emission reduction technologies (e.g., CCS, CCUS, etc.), or negative emissions technologies socially preferred and/ or acceptable?

Onshore wind power and electricity transmission lines are likely to experience the highest barriers to social acceptance in the coming years. These barriers have important system-wide effects, notably distributional effects regarding electricity prices and revenues, effects on the installed capacity of different RES technologies, and effects on the consumer costs of electricity (Bolwig et al., 2020).

RQ80. What are the factors and consequences of social acceptance of energy technologies? How does social acceptance affect distributional welfare across different groups (e.g., consumers and producers) and contexts?

RQ81. What is the social and political acceptance to provide other countries with renewable energy and thus built up more infrastructure faster?

RQ82. Would it be socially acceptable to deploy fjords as pumped storage power plants? Would it be acceptable in Norway to leave oil resources unexploited?

<ins>How to get there</ins>

"*Social acceptance for carbon neutrality and the implementation of necessary measures to achieve it are essential*."

RQ83. What actions and/ or policies could increase the social acceptance of renewables?

RQ84. How is social acceptance affected by contrasting behaviour towards climate neutrality (e.g., opposition towards new renewables infrastructure vs. demand for nature protection)?

Employment and just transition implications

<ins>Where we want to get to</ins>

The effect on employment in conventional energy industries could be important and alternative options should be examined. Based on stakeholders' feedback: "*there is a challenge of how to socio-economically justify the development and implementation of these aforementioned technological solutions; how to substitute in the future the incomes, which so far have been covered by traditional, fossil sectors, like oil and gas sectors in Norway, or how carbon is managed, reduced and also reused for biofuel conversion in the system*."

RQ85. How many new jobs can be created in the renewables sector in order to compensate job losses in fossil fuel industries, especially in Norway? How does the impact on job gains and losses in specific regions, e.g., fossil-fuel intensive regions, differ from wider national impact?

Distributional effects

<ins>Where we want to get to</ins>

"*In the context of achieving Nordic carbon neutrality, there is a lack of clarity regarding distributional effects. More specifically, while decarbonisation is supposed to be a just transition process and have positive effects on creating more and better jobs, there is a lack of evidence, where jobs are created, and, where potentially, not. A bundle of policy instruments across different governance levels is necessary to better account for distributional impacts. The latter might be challenging, because sometimes people from different political parties are in power at the national and municipal levels*."

RQ86. What are the resulting economic implications for consumers from the trade-off between security of supply and desire for green electricity (e.g., welfare impacts across households)?

RQ87. What will be the implications for vulnerable consumers due to the change of the system marginal price and the total system cost (e.g., welfare impacts per income level)? Which policies could support EE investments in energy poor households?

RQ88. In case of increased participation of citizens in the energy system, what are the costs and benefits for all involved stakeholders in social (i.e., welfare distribution), environmental (i.e., total CO_2 emissions by economic sector), and economic terms (i.e., turnover by economic sectors and GDP)?

<ins>How to get there</ins>

Careful policy design can enhance the energy transition process. Which policy instruments/ measures (e.g., CO_2 taxes, green electricity scheme, etc.) are socially accepted or preferred, and under what conditions are they effective?

RQ89. What policies facilitate a fair distribution of costs and, thus, could be socially accepted?

3.3. Continental level case study: “The future of the European energy system- Unveiling the blueprint towards a climate-neutral economy”

In the last two decades the European Union has been a global leader in fighting climate change through its ambitious policies (Oberthür, 2011; Wurzel et al., 2016). Recently, this progressive approach has accelerated and at the end of 2019 European Commission announced The European Green Deal, which is a comprehensive strategy navigating the EU to become the world’s first climate-neutral continent by 2050 (European Commission, 2019). The actions proposed in this document, aiming at increasing the EU’s climate ambition, mobilising industry for a clean and circular economy, building and renovating in an energy and resource efficient way and preserving and restoring ecosystems and biodiversity will lead to the complete transformation of the current energy system. Mobilising additional public and private funding and pushing investments in research and innovation, combined with multiple instruments foreseen in the recovery plan for Europe as a response to the COVID-19 crisis, will give an additional push to this transformation (European Commission, 2020f).

At the same time, the way leading to such deep transformation comprises numerous challenges and uncertainties. For more than twenty years energy system modelling has been in the heart of future European climate and energy scenarios and helped European policymakers to unpack and face those challenges (Süsser et al., 2020). However, models applied in EU policymaking have been criticised for lack of transparency and conservative assumptions (Graf & Buck, 2017). Thus, the new ambitions related to the European Green Deal require better adapted modelling tools for addressing the challenges and uncertainties of energy transition. One of their main desired features is to reflect as precisely as possible the concerns, needs and demands of stakeholders interested in, and affected by, the European climate and energy policies (Gaschnig et al., 2020).

This case study specification creates a basis for identification of critical issues and challenges of the European energy transition for the decades to come. It proposes six different thematic areas, which are a starting point for a further discussion aiming at opening a black box of potential requirements of stakeholders and modellers dealing with future energy systems.

3.3.1. Background on Policies and Targets

Europe aims at becoming the first climate-neutral continent by 2050 and can lead the way by investing in feasible and innovative technological options, empowering citizens by including them in the energy transition, and ensuring social equity for a just transition[11]. Striving towards climate neutrality is the focus of the European Green Deal[12], which proposes measures in line with current and ambitious targets for GHG emissions. The Green Deal includes the 2030 Climate Target Plan, which aims at reducing net GHG emissions by at least 55% by 2030 (from 1990 levels). This is a significant increase relative to the previous target of at least 40%[13], set in the 2030 climate and energy framework of the EU[14]. The Green Deal presented an initial roadmap of the

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[11] https://ec.europa.eu/clima/policies/strategies/2050_en

[12] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[13] According to the 2030 climate and energy framework of the EU, besides the outdated target of at least 40% GHG emission reduction compared to 1990 levels, the other two key targets for 2030 are: **(i)** at least 32% share of renewable energy (**Renewable Energy Directive- RED II**), and **(ii)** at least 32.5% improvement in energy efficiency (**Energy Efficiency Directive- EED**). These two targets are still in effect.

[14] https://ec.europa.eu/clima/policies/strategies/2030_en

key policies and measures needed to transform the EU economy for a sustainable future. The key elements/ policy areas of the Green Deal are (European Commission, 2019):

- Increasing the EU's Climate ambition for 2030 and 2050,
- Supplying clean, affordable, and secure energy,
- Mobilising industry for a clean and circular economy,
- Building and renovating in an energy and resource efficient way,
- Accelerating the shift to sustainable and smart mobility,
- Zero pollution ambition for a toxic-free environment,
- Preserving and restoring ecosystems and biodiversity,
- Fair, healthy, and environmentally friendly food system,
- Financing the transition,
- "Leave no one behind" (just transition).

For achieving climate neutrality, key EU legislation and policies have been outlined in the EU climate action and the Green Deal[15]:

- Reducing GHG emissions of electricity generation, industry, and aviation sectors via EU Emissions Trading System (EU ETS); Contribution of forestry and land use to GHG emission reduction; GHG emission reduction from transport using, for instance, CO_2 emission standards for vehicles,
- Setting national GHG emission targets for non-EU-ETS sectors, such as transport, buildings, and agriculture,
- Boosting EE, renewable energy, and governance of EU countries' energy and climate policies as well as promoting innovative low-carbon technologies,
- Phasing down climate-warming fluorinated greenhouse gases, protecting the ozone layer, and adapting to the impacts of climate change,
- Funding climate action.

Before the Green Deal, the "A Clean Planet for all" document, published in 2018, provided a vision of the economic and societal transformations needed to achieve the transition to net-zero GHG emissions by 2050. The road to a net-zero GHG economy could be based on a set of seven main strategic building blocks (European Commission, 2018):

1. Maximisation of EE benefits including net zero emission buildings (NZEB)
2. Maximisation of the RES utilisation and electrification for full decarbonization of energy supply
3. Carbon-free, secure, and connected mobility
4. A competitive EU industry and the circular economy to facilitate reducing GHG emissions
5. Development of adequate smart network infrastructure and interconnections
6. Exploitation of bioeconomy and creation of carbon sinks
7. Removing remaining CO_2 emissions with CCS

In 2020, a Recovery plan was set by the European Commission, the European Parliament, and EU leaders to enable EU countries to repair the economic and social damage caused by the COVID-19 crisis (European Commission, 2020f). For this task, a total of €1.8 trillion, which is the largest stimulus package ever financed

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[15] https://ec.europa.eu/clima/policies/eu-climate-action_en

through the EU budget, have been reserved. Furthermore, financial support and technical assistance will be offered to help those that are most affected by the energy transition, the so-called "Just Transition Mechanism". At least €100 billion over the period 2021- 2027 will be mobilised for the most affected regions[16]. **Table 10** presents GHG emissions reduction targets by 2030 for the Continental level case study.

Table 10. Overview of the GHG emissions reduction targets by 2030 for the Continental level case study

Country/ Region	GHG emissions reduction target by 2030 relative to 1990 levels
European Union[17]	at least **55%**
Iceland (Government of Iceland. Ministry for the Environment and the Natural Resources, 2021)	**55%** (compared to 2005 levels)
Norway (Norwegian Ministry of Climate and Environment, 2020)	at least **50%** & towards **55%**
Switzerland (Swiss Federal Office for the Environment (SFOEN), 2020)	at least **50%**
UK (UK Government, 2020)	at least **68%**

3.3.2. Energy Scenarios & Narratives

We define scenarios that enable to explore the future picturing of different policy responses to climate change and evolve with different modes of policy implementation. The reference scenario '*current trends*' represents the current progress on implementation of climate and energy policies. The '*climate neutrality*' scenario is linked to the long-term strategy (European Commission, 2020d), and together with the '*current trends*' scenario, this allows to give insights into the impact of proposed policies on the energy system needed to achieve the climate neutrality goal. In addition, we define the '*early neutrality*' scenario where the EU aims to become climate neutral by 2040. The storylines for these scenarios describe the different images of the future, based on different progress of political, social and technological drivers. **Table 11** summarises climate and energy targets of the energy transition by 2030 & 2050 for the different EU case study scenario.

"*Current trends*:" Although the EU is currently a forerunner on climate, it will only implement the current policies defined in the 2030 energy and climate framework. After 2030 no (global) deal is reached on strengthening policies, and climate policy will stay in line with keeping temperature below 2°C. Therefore, the existing policy mix is continued leading to similar annual reductions as achieved in the period between 2020 and 2030. The world is divided, and climate policy is very much a domestic issue. EU citizens only take climate measures, if this is cost-effective with a short payback period, and it does not lead to large layoffs in fossil dependent sectors. In terms of technology, blue and green hydrogen production, and smart grids face large barriers for implementation. Only current renewable technologies such as solar PV, wind and biomass are further implemented, and come down in terms of costs.

"*Climate neutrality*:" The EU implements its 2050 climate neutrality goals that was submitted to the United Nations Framework Convention on Climate Change (UNFCCC) in the Mid-century strategy. Therefore, the total net GHG emissions by 2050 will be around zero. This is also the goal in the sustainable roadmap 'Green Deal' that aims to boost the use of efficient resources, restore biodiversity, and cut pollution (European Commission, 2019). The aggregated impacts of all UNFCCC parties prove to be enough to hold the world well below 2°C or 1.5°C. This includes overshoot and negative emissions in the second half of this century.

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[16] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[17] https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en

Therefore, no ratcheting up of this ambition is necessary. More and more people start accepting the necessity of climate policies, and implementation speed increases. Promising technologies become ready for cost effective implementation, and behaviour changes leading to energy savings slowly settle in.

"***Early neutrality (optional)***:" The world chooses to ensure the 1.5ºC goal of the Paris Agreement, and to only accept a very limited amount or no negative emissions. In addition, the EU is increasing its ambition in line with burden sharing scenarios (Höhne et al., 2019) and the "PAC" scenario[18] (EEB and CAN Europe, 2020). This goal is translated to net zero GHG emissions by 2040 for the EU. The EU ensures that the ambitious climate policy has a bearable impact on all citizens, although large social changes take place. All existing RES technologies decrease in costs quickly, and innovative technologies for negative emissions are scaled rapidly.

Table 11. Climate and energy targets of the energy transition by 2030 & 2050 for the EU case study scenarios

	Past		***"Current trends"***		***"Climate neutrality"***		***"Early neutrality"***
	1990	**2005**	**2030***	**2050**	**2030****	**2050**	**2040**
Total GHG reductions (incl. LULUCF) in **Mt $CO_{2eq.}$**	5413	4940	2870	1950	2435	<25	<25
Reduction 1990 (%)	-	9%	47%	64%	55%	Nearly 100	Nearly 100
Total GHG reductions (excl. LULUCF) in **Mt $CO_{2eq.}$**	5659	5164	3150	2130	2640	(350-500)	(350-500)
Total CO_2 emissions in **Mt $CO_{2eq.}$**	4475	4319	<2400	< 1600	<2000	< 200	< 200

*Main instruments: **ETS:** -43% relative to 2005, **Effort sharing:** 30% relative to 2005, **RED II:** 32% renewable final energy, **EED:** 32.5% EE improvement.
The values in here considered assume that the new targets, approved in September, will also apply to the UK despite having left the EU. It must be noted that the UK has recently approved more ambitious targets by 2030, comprising reductions of up to **68% in comparison with 1990 (Committee on Climate Change, 2020).

GHG emissions reduction targets are divided between **(i)** the sectors covered by the EU Emissions Trading System (EU ETS), **(ii)** non-ETS sectors under the Effort Sharing Regulation (ESR), and **(iii)** land-use related emissions and removals addressed by the regulation on emissions and removals from land use, land use change, and forestry (LULUCF). EU will reduce its GHG emissions from sectors covered by the EU Emissions Trading System (EU ETS) Directive (EU) 2018/410 by 43% until 2030 relative to 2005 levels, and each EU Member State will reduce its GHG emissions from sectors outside the EU ETS until 2030 relative to 2005 levels based on Regulation (EU) 2018/842 (European Union, 2020). The respective targets are presented in **Table 12**.

Table 12. Overview of GHG emissions reduction targets from sectors outside of the EU ETS per country

Country	**GHG emissions reduction target by 2030 relative to 2005 levels**
Belgium	35%
Bulgaria	0%
Czech Republic	14%
Denmark	39%
Germany	38%
Estonia	13%
Ireland	30%
Greece	16%
Spain	26%

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[18] https://www.pac-scenarios.eu/

France	37%
Croatia	7%
Italy	33%
Cyprus	24%
Latvia	6%
Lithuania	9%
Luxembourg	40%
Hungary	7%
Malta	19%
Netherlands	36%
Austria	36%
Poland	7%
Portugal	17%
Romania	2%
Slovenia	15%
Slovakia	12%
Finland	39%
Sweden	40%

3.3.3. Critical issues, Challenges & Research questions

Modelling the deep decarbonisation of the EU energy system poses several challenges, requiring large-scale expansion of renewables, energy savings and electrification of the final consumption, and development of disruptive mitigation options (e.g., green hydrogen and CCUS, etc.) (Fragkos et al., 2021).

In order to uncover the needs of stakeholders, first, we structure the challenges of the future European energy system around six different thematic areas, presented in **Table 13**, stemming from the information about the priorities of the European Commission in the energy realm (European Commission, 2016, 2019) and internal discussion with SENTINEL modellers.

Table 13. Six thematic priority areas included in the Continental level case study

1. **Transforming the power sector: increasing ambitions for GHG emissions reduction & RES targets**
2. **Sector coupling: implementing smart energy systems and accelerating the shift to sustainable mobility**
3. **Decarbonisation of industry and Carbon Capture and Utilization and Storage (CCUS) & Bioenergy with Carbon Capture and Storage (BECCS)**
4. **Modelling energy demand of the building sector- a transition towards zero carbon society**
5. **Environmental aspects & implications, including the circular economy**
6. **Socioeconomic aspects &implications, including recovery packages**

Based on these insights, and in order to identify specific challenges related to these areas, we combine insights from with the theoretical underpinnings presented by the *Three types of knowledge tool*, which “serves reformulating research questions in order to check what (societal) knowledge demands the questions meet.” Next sections shortly summarise each of the thematic areas and propose specific research questions, which could frame further modelling exercises. Similarly, as in the Regional level case study, while using the quotations, we do not indicate a given stakeholder group that provided such expression.

3.3.3.1. Transforming the power sector: increasing ambitions for GHG emissions reduction & RES targets

Decarbonisation of the electricity system

Where we are

Carbon neutrality is linked with the decarbonisation of the power system. Although the share of renewable energy in electricity generation has increased considerably over the last decades, with 2020 being a breakthrough year, in which more electricity in the EU was produced from renewables than from fossil fuels (Agora Energiewende and Ember, 2021), achieving decarbonisation will need a complete transformation of the current system and utilisation of all possible technologies.

Where we want to get to

In October 2020, the European Parliament voted in favour of 60% GHG emission reduction target by 2030 compared to 1990 levels, what is more ambitious than Commission's proposal of 55% from September 2020 (European Parliament, 2020). Parallelly the European Commission has initiated a process leading to a revision of existing renewable energy directive (Süsser et al., 2020), which should increase the overall target of the 32% share of energy from renewables of the EU's gross final consumption in 2030 (European Commission, 2020g).

Stakeholders reflected on how many years are needed for the European energy system to be able to handle a large share (e.g., >70%) of renewables. In their view, "*this could possibly range from 5-7 years up to even 25 years*", due to related challenges, such as "*their intermittency and the uncertainties related to the supply of materials for batteries*." As stated also in (Mikulčić, Baleta, Klemeš, & Wang, 2021), the increase in VRES penetration entails specific challenges related to their intermittency, such as curtailment, optimal use of biomass resources, waste-to-energy technologies, and energy storage. However, they agreed that "*by 2040 more than 70% of energy in the EU can be produced from renewables, but with several stipulations*."

RQ1. What should be the levels of capacity and efficiency increase for wind and solar technologies in 2030 and 2050? What is the potential of self-production technologies (e.g., PV panels installed on the rooftops) in electricity generation?

RQ2. What is the expected increase in installed capacity and power generation from biomass? What kind of feedstock should be utilised for power generation from biomass: woody biomass or waste?

RQ3. What shall be the shares of biogas and biomethane in the fuel basket for power and heat production? What kind of conversion technologies shall be prioritised: combustion or gasification?

How to get there

Decarbonisation of the European power sector, while maintaining reliability, availability, and cost-competitiveness of supply, is highly complex. Realisation of these targets will be related to the development of transition pathways to meet specific technological, social, economic and, political expectations on a European level (Pleßmann & Blechinger, 2017). In order to answer these questions concrete information in regard to governmental plans and regulation is required.

RQ4. How will the EU coordinate the electricity market design?

As mentioned by stakeholders, "*achieving the decarbonisation objectives will depend on the advancement of fossil fuel dependent sectors (e.g., aviation, heavy industries, etc.)*." Also, "*the RES target could encompass EU as a whole, but some countries and regions will be far from that target*."

RQ5. What are the necessary investments and policies in place to accommodate the ambitious shares of RES in the power sector (e.g., more than 70% by 2040, etc.)? What should be the timing of investments in promising renewable technologies to avoid causing technical lock-ins?

RQ6. Can RES targets of some European countries be achieved by installation of renewables in neighbouring countries and importing electricity from them?

Sustaining high levels of natural gas power plants' capacity may challenge the power sector in the future, since they increasingly generate less electricity per capacity unit and will be mainly utilised as capacity related service providers for the power system (Capros et al., 2018). Clean coal utilisation and CCS could maintain the sustainability of thermal electricity generation (Yu, Fang, & Dong, 2020).

RQ7. What would be the evolution of natural gas power dispatch in the coming years? What shall be an annual increase of efficiency for the gas-fired power plants? Shall they implement CCS?

RQ8. Would the implementation of clean coal utilisation and CCS lead to maintenance of coal-fired power plants?

The workshop participants indicated that "*hydrogen can also be used directly in thermal plants instead of natural gas and reversible fuel cells may be used to go from hydrogen to electricity*."

RQ9. What should be the adoption rate of implementing hydrogen in thermal plants instead of using natural gas? How efficient would it be to use reversible fuel cells to convert hydrogen into electricity?

Stakeholders also emphasised in changing and adapting specific energy infrastructure related to risk issues and possible accidents, as in the case of gas and hydrogen grids.

RQ10. What is the risk of accidents related to implementation of different energy technologies, like gas or hydrogen?

Flexibility of the electricity system

Where we want to get to

Several European countries face the challenge of having the necessary flexibility to balance the electricity system. Flexibility consumption and the role of the aggregator, as an entity which can collect and pool individual customers' flexible consumption, are key elements of the Clean energy for all Europeans package (Carlini, Schroeder, Birkebæk, & Massaro, 2019). Stakeholders argued that "*the main obstacle in decarbonising the power sector will be the lack of flexibility mechanisms in place*."

How to get there

Concerning different options for flexibility mechanisms in 2030, stakeholders emphasised mostly in electricity storage, such as pumped hydro, batteries, etc. Regarding the long-term perspective, stakeholders mentioned that "*focus should be given on hydrogen, which can be potentially imported from Middle East and Africa, when it will become a competitive flexibility option*.". Finally, it was also mentioned that "*demand-side flexibility and heat storage should be considered as potential flexibility mechanisms*."

RQ11. What power sector flexibility mechanisms should be in the focus of energy planning/ modelling as renewables increasingly become the dominant component of the power system?

According to stakeholders, "*it is cheaper to store energy as heat, liquids, or gaseous fuels compared to electricity in the form of batteries or pumped hydro storage. For example, the EU's long-term strategy up to 2050 assumes that energy storage in 2050 based on hydrogen and e-fuels ranges between 65TWh and 220TWh. In overall terms, we need to implement all the steps necessary for a smart and integrated renewable energy system, thus, avoiding a sole focus on electricity grids.*"

RQ12. Regarding the different energy storage carriers, what will be the necessary energy capacities of large-scale storage (e.g., batteries, hydro, heat storage, etc.), synthetic fuels, and hydrogen by 2030 and 2050?

Decentralisation of the power sector

Where we want to get to

Decreasing costs of RES foster decentralisation of the power system. However, scaling-up RES could lead to negative prices for generated electricity from intermittent sources (Swain & Karimu, 2020). Thus, "*the electricity system should have the capacity to handle the different timescales of renewables' variability and maintain stability, due to decentralised power production*."

How to get there

Stakeholders reflected on what degree of decentralisation is actually feasible and useful and mentioned key aspects relevant to this issue, such as "*advancing digitalisation, the degree of electricity self-production, the level of electrification of industry, the role of hydrogen in it, technological lock-ins as well as possibilities of power exchange with other jurisdictions, like Iceland or those located in North Africa*."

RQ13. What would be the feasible degree of decentralisation in the EU electricity system?

RQ14. To which extent will digitalisation of power generation and distribution enable a self-optimising power sector?

RQ15. What is the potential for power exchange with other jurisdictions, like Iceland or those located in North Africa?

Transmission and distribution

Where we want to get to

The unpredictable nature of wind and solar power generation rises complexity and risks associated with the management of transmission infrastructure (Shivakumar, Dobbins, Fahl, & Singh, 2019). Differentiated views regarding the role of the European transmission system were presented during the EU case study workshop. Some stakeholders argued that "*international HVDC transmission will become more relevant by 2030 in the electricity system*", while others indicated the opposite due to the ongoing decentralisation. However, all stakeholders agreed that "*by 2030 the international HVDC transmission will be a more important component of the electricity system than AC transmission*." With regards to transmission in the long-term, stakeholders unanimously claimed that "*in 30 years, the European power system will depend more on international HVDC transmission interconnectors which will handle renewable variability*." Furthermore, bulk energy storage systems could improve grid stability and facilitate avoiding transmission congestion issues (Xu & Liu, 2020).

RQ16. What will be the capacity of the electricity system to handle a large share of renewables in 10, 15, and 20 years?

RQ17. How should the intra-continental grid connections be structured to capitalise on weather system correlation/ anti-correlation, over-capacity of renewables, and large-scale load shedding? How should the distribution grid be structured by 2030 and 2050 to avoid possible bottlenecks?

How to get there

RQ18. What should be the level of investments into the grid infrastructure?

RQ19. Is the large-scale transmission (i.e., reinforcement of transmission lines to transfer electricity generation across the EU) a possible future, at all? What is the future of the European transmission system in light of expected increases in total electricity demand and regionalisation of supply?

3.3.3.2. Sector coupling: implementing smart energy systems and accelerating the shift to sustainable mobility

System integration

Where we want to get to

Electrification of demand sectors is one of the pillars in the system transformation towards carbon neutrality. As mentioned by stakeholders, "*system integration will help lower the strain on the electricity grid coming from an increased heating and transport demand*." To achieve this, several challenges need to be overcome, and digitalisation is expected to offer a helping hand in this process. A successful integration of the sector coupling approach to the EU energy and climate policies could focus on four building blocks: **(i)** infrastructure planning; **(ii)** system and market operation; **(iii)** regulatory framework; and **(iv)** research, development, demonstration and deployment (Olczak & Piebalgs, 2018). While in previous years the European Union started a set of initiatives, which should facilitate the sector coupling (Erbach, 2019), it was not until July 2020 that the European Commission presented the Strategy for Energy System Integration (European Commission, 2020e), signifying the beginning of this process.

RQ20. How many additional kilometres of electricity grids in the EU are needed to foster electrification and realise climate neutrality by 2050? By how many kilometres could this amount be reduced by implementing smart and integrated renewable energy systems?

How to get there

Stakeholders indicated that it is important to consider how sectors will burden themselves with the energy transition costs across different geographical contexts.

RQ21. How should electricity production be allocated across demand sectors?

RQ22. How will the energy transition costs be distributed across different sectors and geographical settings? What will be the impact of system integration on the attempt to lower the strain on the electricity grids?

Decarbonisation of heating/ cooling

Where we want to get to

"*To achieve climate neutrality, the heating and cooling sector needs to transition away from using fossil fuels, like gas and oil, and be designed to fit a development towards smart energy systems. This will require development of 4th generation district heating networks and implementation of heat pumps, waste heat, and thermal storage within the district heating grids*."

RQ23. How should the heating and cooling sector be structured across different European countries to accommodate smart energy systems?

RQ24. What would be the total cost of introducing district heating and implementation of heat pumps, waste heat, and thermal storage in the EU by 2050?

Stakeholders mentioned that "*the high temperature heat could be used for electricity generation and excess heat resulting from hydrogen production could be utilised in district heating grids*."

RQ25. What amount of the high temperature heat stemming out of the industrial processes could be turned into electricity?

RQ26. What is the potential of using excess heat from hydrogen production in the district heating grids?

How to get there

Heating strategies for Europe should be established and the potential for district heating and heat pumps should be investigated. By achieving system integration and making all sectors interact with each other, the potential investments needed can be minimised.

RQ27. What should be the adoption rate of heat pumps in European households instead of ineffective heaters by 2030 and 2050 to decarbonise residential buildings?

Stakeholders were not sure whether some of the industrial processes will be able to rely only on hydrogen, since "*hydrogen poses potential risks, which could make it more relevant to include it in the production of e-methane and e-fuels*", or whether they will still need carbon fuels. They noticed that "*a possible solution would be to use heat pumps for lower temperature industrial processes*."

RQ28. Which industrial processes could be decarbonised via hydrogen and which will require the use of fossil fuels? Could heat pumps be used in lower temperature industrial processes?

RQ29. What is the necessary P2X infrastructure to satisfy the needs of industry and power plants?

Decarbonisation of transport

Where we want to get to

A part of achieving climate neutrality is related to a shift to sustainable and smart mobility- that would require 90% reduction in transport emissions by 2050 (European Commission, 2019). According to stakeholders, "*electric vehicles and P2X infrastructure have to be implemented to fit both passenger transport and heavy transport needs*."

RQ30. What should be the share of electric vehicles and plug-in hybrids in the total car fleet for by 2030 and 2050?

Stakeholders also raised a point regarding the role of the railway systems in the decarbonisation of the transport sector.

RQ31. What will be the emissions reduction due to the exploitation of railway systems?

How to get there

Achieving 90% reduction in transport emissions by 2050 requires specific investigations of how the transport sector can be decarbonised and the resulting P2X demands. That generates further questions:

RQ32. What should be the pace of exchanging the existing car fleet with electric vehicles by 2030 and 2050 to achieve this objective? What are the other options to decarbonise the transport sector, except for electric vehicles?

RQ33. What should be the post 2020 CO_2 emission standards for fossil-fuelled vehicles?

RQ34. What should be the increase in efficiency (fuel consumed per km) for different types of vehicles by 2030 and 2050?

Regarding the decarbonisation of the transport sector, stakeholders mentioned challenges, like post-COVID-19 pandemic's consequences. For example, they considered how the pandemic will affect transport patterns, such as the future demand and capacity of public transport.

RQ35. How will the COVID-19 pandemic influence the transport patterns? Will there be a shift away from the public transport?

"*Heavy goods vehicles (HGV) need to be effectively decarbonised using electricity and batteries based on their technical requirements (i.e., weight, cargo and autonomy)*." Stakeholders pointed out that "*electrifying freight using battery electric trucks is feasible, since this technological option can cover most of short distances*." However, stakeholders argued that "*there is no certain answer regarding long distance trucking*." The issue mentioned is that "*car technology drives the development in the whole road transport sector, and right now this looks to be purely electric going into 2050*." Thus, "*hydrogen trucks are dependent on hydrogen cars* *being a widespread solution, which is not the outlook right now. E-fuels might be a solution if direct electrification is not possible*."

RQ36. Are batteries feasible for the long-distance trucking?

Stakeholders argued that "*hydrogen passenger cars will become feasible and that could be a first step towards hydrogen-based trucking*." They divided between heavy and light trucks because they have different options to shift from fossil fuels. "*In the case of heavy trucks, additional factors determining the technological choices' availability will need to be considered. For example, some heavy trucks are mainly for driving short distances, allowing them to use batteries more easily, as opposed to those driving long-distances*."

RQ37. Are hydrogen passenger cars feasible? To what extent could trucking be based on H_2?

RQ38. What are the options for short distance (e.g., shifting to batteries, etc.) and long distance heavy trucking?

During the workshop, it was mentioned that "*a different solution could be to build electric roads*."

RQ39. What would be the impact of the electric roads on decarbonisation of the transport sector?

"*An additional challenge arises in the large demand of alternative fuel production for the aviation and marine industries. Such a large share of power will require a smart allocation of electricity production among different sectors, which should also be adequately reflected and improved in existing energy models*."

RQ40. How much power will be needed to produce fuels for aviation and marine?

3.3.3.3. Decarbonisation of industry and Carbon Capture and Utilization and Storage (CCUS) & Bioenergy with Carbon Capture and Storage (BECCS)

Decarbonisation of industry

Where we are?

The decarbonisation of industry and, in particular, heavy industry could be one of the biggest challenges on the road to a climate neutral world. In this context, the European Commission published in March 2020 the new industrial strategy for Europe (European Commission, 2020a), which underlines the upcoming role of industrial value chains or zero-carbon steel making.

Where we want to get to

"*Industrial decarbonisation will require electrification, hydrogen use, biomass as an input to produce biofuels/ biogas, utilising both mechanical and feedstock recycling of existing plastic as well as Carbon Capture Utilisation and Storage (CCUS)*." Electrification of industry is expected to be achieved through various low-carbon technologies (e.g., motors, pumps, compressors, etc.) (Mikova, Eichhammer, & Pfluger, 2019).

RQ41. What will be the levels of electrification of different industrial subsectors by 2030 and 2050 and what role would hydrogen and biomass play in decarbonisation of these subsectors?

How to get there?

Stakeholders argued that "*industry will be incrementally using fewer fossil fuels, impacting in this way the refineries, whose capacity will decline, and electrification of transport will have an additional effect to this trend. However, as oil is also utilised for plastic production, some clusters will remain (e.g., in Belgium)*."

RQ42. How would refineries' production be affected due to the decarbonisation of industry as well as the electrification of the transport sector?

"*It is very difficult to foresee the shares of different fuels for the whole industrial sector in Europe, because it greatly depends on the industry type. For example, CCS will not be applied to the paper and pulp industry, as this industry will mostly utilise biomass with a minor share of fossil fuels*." Stakeholders added that "*the steel* *subsector will likely be decarbonised via hydrogen*", which has been also reported in (Blanco, Nijs, Ruf, & Faaij, 2018). Furthermore, "*biomass will be used in the chemical industry; however, it will be impossible to fully resign from carbon*." Currently, "*different sectors and different countries are testing and developing different options, but it is not clear which choices will become mainstream*."

RQ43. How and at what level could different industrial subsectors be decarbonised by 2030 and 2050? What should be the pace of electrification of heat production in different industrial subsectors?

Stakeholders mentioned that "*the industrial sector asks governments for financial support and funds to invest in new technological solutions, such as for feedstock recycling of plastic*." Nevertheless, "*there is a lack of clear commitment from industry to share such costs in order to remain competitive*."

RQ44. What are the required financial resources to decarbonise the EU industry?

"*It is very challenging to explicitly evaluate whether some European countries will push for an early decarbonisation, because different EU member states represent different "decarbonisation speeds"* ", the so called multi-speed energy transition in Europe [see: (Mata Pérez, Scholten, & Smith Stegen, 2019)]. "*The decarbonisation commitment will depend on the industrialisation levels, the available RES potential, and the characteristics of the current electricity markets*." Stakeholders agreed that "*the European Green Deal is the main driver pushing the industry towards decarbonisation and the introduction of a carbon border adjustment mechanism or a labelling system could contribute to that*."

RQ45. What will be the speed of industrial decarbonisation in different European countries? Which regulations and policies will be necessary for the decarbonisation of the European industry?

Carbon Capture Utilization and Storage (CCUS) & Bioenergy with Carbon Capture Storage (BECCS)

Where we want to get to

Technologies related to CCUS as well as BECCS could facilitate industrial decarbonisation. In order to achieve climate neutrality by 2050 it has been estimated that utilisation of technologies related to CCUS would allow to store between 45-235 Mt of CO_2 per year (Material Economics, 2019).

How to get there

"*There are certain risks related to CCS technology and some of the countries are not keen to invest in it, but it will presumably become commercially viable. Furthermore, CCS can be combined with hydrogen as complementary technologies in order to decarbonise different types of industries, such as the cement sector. The extent of CCUS utilisation depends on emissions-related regulations. In the future, the captured* CO_2 *could be used for fuel production*." BECCS utilisation could lead to negative emissions that enable positive emissions in sectors, where it is more expensive and difficult to decarbonise (Thomaßen, Kavvadias, & Jiménez Navarro, 2021).

RQ46. In which industrial sectors could CCUS technologies be an efficient emissions mitigation option, and when would it become commercially viable? What is the expected time horizon for BECCS technology in energy industries?

Stakeholders noticed that "*there are already CCS projects being developed in the North Sea, which have potential to utilise* CO_2 *produced in industrial clusters in Norway, Belgium, the Netherlands, Germany, and the United Kingdom and thus* CO_2 *could be transported either by pipelines or by ships*."

RQ47. What would be the most viable way to transport CO_2?

Hydrogen

Where we want to get to

"*Hydrogen and electrification will play an important role in the fuel basket of the industrial sector. This can be accomplished on a large scale, helping to transition away from coal and coke feedstock in heavy industries, such as in the steel subsector*."

<u>How to get there</u>

Stakeholders added that "*the foreseen increase in hydrogen production creates a competition between the means of its use*." On the one hand, "*it can be utilised for electricity production*", but on the other hand, "*it can be used as energy carrier to replace natural gas in the transport sector, stationary combustion sources, etc.*". Yet, they pointed out that "*hydrogen use creates other opportunities, as in the case of converting hydrogen back to electricity with fuel cells or using it as an intermediate for chemical and fuel production*" [see also: (Blanco et al., 2018)]. "*In that process, water is produced to be used as a feedstock in other industries, such as in textile production, instead of depleting ground water. Another opportunity stemming from the electrolysis process relates to pure oxygen production*."

RQ48. To what extent could water produced as a side product of converting hydrogen into electricity be used in some industrial processes? Conversely, to what extent could oxygen, produced in the electrolysis process, be used in other industrial applications?

Stakeholders reported that "*the EC is carrying out studies investigating how to adjust the natural gas pipelines for hydrogen and is also working on the legal aspects accompanying these technological developments*."

RQ49. When could the natural gas infrastructure (e.g., natural gas pipelines) be adjusted to hydrogen needs?

3.3.3.4. Modelling energy demand of the building sector- a transition towards zero carbon society

Decarbonisation of the building sector & energy efficiency

<u>Where we are</u>

The building sector in the EU is one of the largest energy consumers, responsible for 36% of the EU's GHG emissions (Spyridaki, Stavrakas, Dendramis, & Flamos, 2020). Considering that the EU has a relatively high share of old and inefficient building stock, this sector plays a crucial role towards climate neutrality. In that context, the European Commission published in October 2020 a strategy to boost renovation of buildings to save energy and stimulate the economic growth (European Commission, 2020b). The so-called "Renovation Wave" is targeting EE improvement, addressing in parallel the health and well-being of vulnerable citizens, while reducing their energy bills. Resource efficiency is a prerequisite in the construction and renovation process, which should be accelerated– currently only 11% of the existing EU building stock undergoes some level of renovation annually (European Commission, 2020b).

<u>Where we want to get to</u>

In the Renovation Wave, the EC indicates that in order to contribute to the general 55% emissions reduction target by 2030, the buildings' GHG emissions should be reduced by 60%, their final energy consumption by 14%, and energy consumption for heating and cooling by 18% compared to 2015 levels (European Commission, 2020b). "*Decarbonising the energy sector by 2050 will require better balancing of energy demand*", since the seasonality of heat demand will induce great challenges in the power system at deep heating sector decarbonisation levels (Chen, Jensen, Kirkerud, & Bolkesjø, 2021).

RQ50. What should be the RES share in the final energy consumption of the building sector to achieve the buildings' GHG emissions reduction by 2030?

<u>How to get there</u>

Stakeholders mentioned that "*heating and cooling are the most important aspects to target energy consumption and the emergence of new appliances could also affect the energy consumption trends*." Fuel switch in heating and cooling, e.g., via electrification of heat supply or increased penetration of heat pumps, can further contribute to reduction of energy demand in the building sector (European Commission, 2018). Furthermore, "*behavioural aspects affect energy usage in regard to temperature settings for heating and cooling, so it is important to include this aspect in models, like EUCalc*".

RQ51. What would be the shares of heating and cooling in final energy consumption of the building sector by 2030? What is the expected CO_2 emissions reduction in this subsector? What are the most efficient temperature settings for heating and cooling, which would maximise CO_2 reduction?

"*There are several region-specific factors, including weather differences and effects on implemented measures, traditional architecture, RES potential for heating (e.g., via PV panels), electrification trends, developments in population and urbanisation, and consumer behaviour, which affect energy demand in the European countries*."

RQ52. How would energy demand evolve under the effect of various region-specific factors in European countries by 2030 and 2050? How would these factors affect energy-related behavioural patterns and use?

RQ53. What is the potential of installing rooftop PV panels to reduce the CO_2 emissions from the building sector? How would different renewable energy potentials impact the heating and cooling subsector in different European countries?

RQ54. How would different weather patterns affect the efficiency, operation, and diffusion of heat pumps and PV panels in different regions?

RQ55. What is the potential of geothermal energy to cover heat demand in Europe by 2030 and 2050?

The uptake of energy efficient equipment following the EU energy labelling and eco-design legislation can effectively contribute to further reduction of energy demand. The energy labelling and eco-design regulations are estimated to deliver annual energy savings of over 600 TWh in 2030 (European Commission, 2018).

RQ56. Which EE measures have the highest potential to reduce energy consumption and, thus, to contribute to higher energy savings? How would the emergence of new technologies/ appliances impact the energy consumption trends?

According to stakeholders, "*behavioural aspects could also be sector-specific and thus should be considered when modelling the behaviour of prosumers and consumers and the efficacy of increasing consumer awareness*." They also discussed about other relevant aspects, such as the demographic factors of aging populations and the percentage of building owners versus renters.

RQ57. What would be the impact of increasing environmental awareness of consumers, the building stock's ownership structure, and investment decisions (e.g., regarding the distribution grid, etc.) on energy demand of the building sector? To what extent could the investments in the distribution grid improve the overall system's performance and optimise it?

RQ58. Which policies (e.g., economic incentives, etc.) would facilitate companies and households changing their direct and indirect energy consumption behaviour in the short- and long-term perspective?

Moreover, "*resilience and adaptation of infrastructure are paramount to withstand unprecedented events caused by climate change. Upgrading and digitalising old building systems create more balanced consumption. The societal drivers for renovating old buildings also have distributional effects on household spending and savings as well as macroeconomic effects for the public*."

RQ59. What should be the pace of upgrading and renovating the current building infrastructure to make it resilient to climate change events? Which business models could incentivise people investing in the necessary technological infrastructure?

Also, "*real estate markets could benefit from successful implementations of EE measures. Business models will be needed to incentivise people investing in the necessary technological infrastructure*."

RQ60. What effects would the EE measures have on the real estate markets?

RQ61. What types of policy measures could lead to behavioural and lifestyle changes as well as implementation of EE measures? Which incentives could be the most successful?

As mentioned during the workshop, "*in the building sector consumers will become prosumers and the next challenge is to create Positive Energy Districts (PEDs)*", i.e., districts that produce more energy than they use (Paci, Bertoldi, & Shnapp, 2020). PEDs can be developed by connecting the individual net zero energy buildings (NZEBs) to smart grids, what would result in creating positive energy buildings (PEBs), which through their contribution to the energy support of other buildings, produce more energy than needed (Magrini, Lentini, Cuman, Bodrato, & Marenco, 2020).

RQ62. How many Positive Energy Districts in the EU would be required to effectively contribute to energy demand reduction? What should be the geographical distribution of Positive Energy Districts across European countries?

Digitalisation

Where we want to get to

"*Digitalisation will be instrumental for the future decarbonisation of the EU building sector. It enables the user to easily control their heating and cooling appliances, increasing both energy efficiency and consumer awareness*."

How to get there

Participants stressed that "*the primary step towards digitalisation should be the introduction of smart metering throughout the EU as well as to monitor its effects on consumer awareness and behaviour*." Smart meters and grids facilitate data collection regarding the state of the grid and user consumption. These data could be inputs for the emergence of new business models, optimising in this way the energy system (Cambini, Congiu, Jamasb, Llorca, & Soroush, 2020).

RQ63. What possible changes in energy use patterns would result due to digitalisation (e.g., remote control, IT systems, etc.)? What could be the reduction of energy demand by 2030 and by 2050 due to remote control options of home appliances and upgraded IT systems?

RQ64. How would smart metering influence the energy demand and consumers' awareness regarding their energy use by 2030 and by 2050?

Stakeholders also considered demand-response applications, time-of-use incentives (i.e., dynamic tariffs), Pay-for-Performance (P4P) schemes, and third-party investments as drivers for further digitalisation applications. When dynamic tariffs are put in place, marketing and awareness raising campaigns will be very important for consumer engagement (Shivakumar et al., 2018).

RQ65. How could the P4P schemes and third party investments contribute to the digitalisation of the European building sector?

RQ66. What are the technological options to combine Demand-Response applications with time-of-use incentives?

"*Creating the building as an energy hub not only optimises the network but also provides greater advantages outside of the building sector. Digitalisation should be combined with charging-discharging patterns of EVs to enable them to act as electric storage facilities*."

RQ67. What is the potential of charging EVs in buildings by 2030 and 2050? How would electric vehicles charging and discharging patterns influence the energy demand peaks?

3.3.3.5. Environmental aspects & implications, including the circular economy

GHG emissions, carbon leakage, and air/ water pollution

Where we want to get to

Stakeholders mentioned that "*that the current GHG emission target of 55% by 2030 is not ambitious enough, and, to achieve climate neutrality, it should be increased to 60%*." They added that "*having an EU-wide target means different repercussions for European countries. To achieve this target, adequately designed regulatory frameworks for all sectors as well as more interconnections between European countries would be required*."

RQ68. How should the EU member states cooperate to realise a higher GHG emission reduction target? Is climate-neutrality by 2050 in the EU viable, affordable, and sustainable in the long run (Capros et al., 2019)**?**

RQ69. To what extent could more interconnections between European countries lead to higher emissions reduction? What would be the costs for the required grid infrastructure?

RQ70. What would be the environmental impacts of developing the necessary transmission and distribution lines?

RQ71. What would be the resulting carbon leakage under the EU ETS in 2030? Which would be the main countries/ regions where it would be concentrated?

Moreover, "*in air pollution hotspots, the ambient air is polluted by NOx, SOx and particulate matters emissions, causing severe human health problems*." Applications using biomass, such as BECCS, could enable better control of air pollution and its related damage costs (Korkmaz, Gardumi, Avgerinopoulos, Blesl, & Fahl, 2020).

RQ72. What kind of pollutants and at what levels would be produced by different energy technologies and sectors in 2030? What would be the health impacts in different air pollution hotspots?

Raw material constraints, water resources, and circular economy

Where we are

As presented in the "*Circular Economy Action Plan*" published in March 2020 (European Commission, 2020c), 50% of total GHG emissions and 90% of biodiversity loss and water stress come from the extraction and processing of different resources.

Where we want to get to

The ambition of achieving climate neutrality by 2050 must be linked with the decoupling of economic growth from resource use by, for example, keeping resource consumption within planetary boundaries. Issues like domestic and imported supply constraints relating to critical raw material supply as well as the ongoing attempts to reduce the European consumption footprint and double circular material use rates in the coming decade must be considered. In a decarbonised, circular Europe, the policy targets for a low-carbon, circular and bioeconomy must be coherent with one another. The participants indicated that "*the increasing lifetime of technologies and appliances would substantiate the circular economy goals*" and agreed on the importance of securing the supplying raw materials.

RQ73. What would be the effect of a supply restriction of raw materials and intermediate products needed for RES technologies?

The manufacturing of clean energy technologies increases demand in mineral and energy resources and, thus, the total resources required for the European energy transition should be identified (Mikulčić et al., 2021). During the workshop, stakeholders argued that "*the development of new energy technologies will be linked to an intensified extraction of resources*."

RQ74. What would be the demand for total resources and rare-earth elements to cover the production of RES technologies by 2050?What would be the annual life-cycle emissions for the manufacture of solar panels, wind turbines, and batteries for EVs?

How to get there

The role of the water-energy nexus should be further researched in the context of the European energy transition, as a future energy system with a higher RES share should reduce water losses. The synergies of sustainable water and energy supply, considering water sector's flexibility and its compatibility with inherent intermittency of VRES, should be studied (Mikulčić et al., 2021).

RQ75. What are the impacts of the decarbonisation of the European energy system on water resources?

"*CCUS technology has potential to reduce resource demand, as in the case of using bio-based carbon for the plastic production*." Specifically, the stakeholders argued that "*the application of CCUS could contribute to a 90% recycling rate in industry, reducing in this way plastic waste*."

RQ76. To what extent could CCUS contribute to the reduction of necessary resources used for plastic production? What would be the annual reduction in plastic consumption based on a 90% recycling rate of the industry by 2030?

Impacts related to the use of batteries and RES

How to get there

With regards to electricity storage, stakeholders pointed out that "*there are substantial differences in environmental impacts when it comes to installing batteries behind the meter or front the meter. This relates to system efficiency and type of technologies avoided by the use of storage (e.g., gas plants). Additionally, putting batteries behind the meter is more difficult to control, therefore it is better to connect rooftop PV to the grids, rather than use battery storage*." Another concern related to behind-the-meter use is related to prosumers' behaviour (Cambini et al., 2020).

RQ77. What are the environmental advantages and disadvantages of installing batteries behind the meter and in front of the meter? What is the most environmental-friendly way of using them?

Participants also discussed topics related to the type and scalability of energy systems. This discussion included storage, ranging from large systems, such as hydro, to systems focusing on domestic, small-scale solutions, such as batteries, which constitute the most common and efficient storage method for small-scale power needs (Dehghani-Sanij, Tharumalingam, Dusseault, & Fraser, 2019). In this context, they indicated that "*small-scale solutions could bring large-scale consequences related to employment and investment rates, participation in the market, and the security and stability of the whole system*." They mentioned that "*it would be beneficial to compare the environmental effects of the centralised and decentralised systems*."

RQ78. What are the environmental impacts of the deployment of small- and large-scale RES and storage systems?

Land use and biomass

Where we are

Land use constraints- particularly in relation to increased biomass production, but also including solar and wind farms- pose a challenge in the way leading to a decarbonised future. Sustainable biomass supply is limited and there are controversies around land-use and emission impacts for some biomass types (Chen et al., 2021).

Where we want to get to

Stakeholders highlighted that "*energy and ecological systems are strongly interrelated. For example, an increase in biomass production or the development of solar and wind farms can lead to externalised environmental impacts related to land-use constraints*."

RQ79. What are the resulting environmental impacts in terms of land use due to the development of RES infrastructure?

"*Biomass can be used for the development of several products, such as fine chemicals, food, fibre, fertilisers, and fuels, and different sectors compete for biomass use, with some industries being still strongly dependent on bioenergy*." Regarding use of biomass for food, shifting towards more vegetarian and lower in meat diets could substantially help mitigate climate change (Strapasson et al., 2020).

RQ80. What environmental impacts are created due to biomass use for the development of fine chemicals, food, fibre, fertilisers, and fuels as well as due to forestry, food crops and energy crops?

RQ81. What will be the total demand for biomass for energy production by 2030 and 2050? What are the environmental effects of biomass' use among different sectors? Which industries will be less dependent on biomass?

How to get there?

Afforestation of surplus land could be key to reduce EU GHG emissions (Strapasson et al., 2020). Workshop participants mentioned that "*100% sustainable forestry would play an important role concerning land use*."

RQ82. What should be the annual uptake of afforestation as potential means of offsetting or reducing a part of GHG emissions? What would be the land-use effects caused by introducing 100% sustainable forestry?

RQ83. What would be the annual emissions from non-ETS sectors and LULUCF?

3.3.3.6. Socioeconomic aspects &implications, including recovery packages

Just transition, job creation, and distributional effects

Where we are

The way to a decarbonised energy system should remain socially sustainable, meaning a just participation of all members of the society, and a fair distribution of costs and benefits should be guaranteed. To make it happen the EU established the "Just Transition Mechanism." The mechanism addresses the social and economic effects of the transition towards a climate-neutral economy, is supposed to ensure fairness, and is built on three pillars: **(i)** the "Just Transition Fund", **(ii)** the InvestEU "Just Transition Scheme", and **(iii)** the public sector loan facility provided by the European Investment Bank. Through these pillars at least €150 billion should be mobilised over the period 2021-2027 (European Commission, 2020h).

Where we want to get to

Stakeholders expressed positive opinions regarding job creation resulting from the implementation of the European Green Deal. They referred to the creation of new jobs related to demand-side management, net metering, services related to the hydrogen technologies, and development of RES technologies and grids. According to (Fragkos & Paroussos, 2018), the Clean Energy Package context will lead to substantial rise in RES jobs (850,000 in 2030 and ca. 1.85 million in 2050), with most of them relating to PV installations (the PV sector is considered an important job creator (Jäger-Waldau, Kougias, Taylor, & Thiel, 2020)), biofuels production, and wind turbines manufacturing and installations. On the contrary, jobs in conventional energy supply sectors will be lost, especially in coal mining, refineries, and refuelling stations. Overall, the net effect of RES expansion on energy-related employment will be positive (about 200,000 additional jobs in 2050) (Fragkos & Paroussos, 2018).

RQ84. How many jobs in the RES sector should be created in various European regions and what share of those should be within energy communities?

RQ85. How many jobs could be created due to the adoption of novel technologies?

How to get there?

Stakeholders mentioned specific challenges, such as phasing-out coal, which would mean that the unemployment among coal sector workers will increase before they will be even able to find jobs in the RES sector. "*That will have additional effects on the income of whole regions and, consequently, on other subsectors of local economies. Thus, the future modelling studies should investigate regional effects on unemployment and job creation, including their spatial dimension, instead of aggregating them at the national or European level. This is particularly important due to the uneven distribution of costs and benefits that determine the acceptance of the energy transition and specific technologies*." As hydrocarbon-related jobs are geographically concentrated, climate policies will severely affect carbon-intensive communities, which should replace eliminated jobs and retrain workers (Fragkos & Paroussos, 2018).

RQ86. What should be the annual pace of replacing jobs in fossil fuel sectors by jobs in RES sector in order to not create higher unemployment rates in the energy sector?

RQ87. How many workers from the coal, gas, and nuclear sectors should be reskilled annually to fulfil the employment needs in the RES sector?

Stakeholders suggested that "*in order to guarantee a just distribution of costs and benefits, significant funding will be needed. A substantial share of money (70-75%) should be mobilised by private funds and the EU member states should guarantee the rest (25-30%)*." To give confidence to investors, specific financial instruments could be required, e.g., to guarantee uniform access to low credit risk financing for RES projects in all European countries (Jäger-Waldau et al., 2020). It was also mentioned that "*some of these funds should be redirected to incentivise reskilling of the workers, in the light of fast RES deployment and coal, gas and nuclear phase-outs*."

RQ88. What funds needed to achieve climate neutrality should come from private investors and from European countries? What should be the shares of the total budget utilized for climate neutral investments for small, medium, and large companies?

RQ89. Should the transition funds be extended for key emitting industrial sectors and the oil value chain?

RQ90. How would the coal phase-out affect regional economies and the countries' budgets?

The EU should ensure that the economic benefits of renewable energy will reach all its member states (Mata Pérez et al., 2019). "*Currently, there is a competition among the member states based on the natural split of RES and subsequent funds, whereas more cooperation and coordination would be needed to fulfil higher targets*." Stakeholders shared that "*although all Nordic countries are perceived as frontrunners in achieving carbon neutrality, they are facing internal challenges and conflicts in that manner. For example, Sweden* *would prefer to set more ambitious climate targets for the whole EU, while in Norway the energy sector is keen to decarbonise, whereas industrial sectors are rather sceptical.*"

RQ91. Where is it most economically viable to build storage and RES infrastructure? How would the distributional effects of the RES funds look like?

Stakeholders reflected that "*just transition aspects will be relevant for energy communities that are expected to develop in the next decades*." Nevertheless, "*in order not to hinder their growth, increased digitalisation's investments are needed. For example, in some European regions the internet connection is still weak, and a reliable and fast internet will be essential to efficiently manage energy flows and enable an effective demand-side management*." They also noted that their development is also a matter of incentives, as in the case of demand-side management. Except for the lack of incentives, collective prosumers face other regulatory challenges, such as not having the capacity to legally set up an energy community and the reduction or removal of existent incentives, such as FITs (Inês et al., 2020).

RQ92. What should be the necessary digital infrastructure in different European regions in order to guarantee an efficient demand-side management?

RQ93. Which regulations and policies would incentivise the creation of energy communities most efficiently?

COVID-19 implications and recovery funds

Where we are?

"*The significance of just transition and job creation moved even higher up the political agenda as a consequence of severe effects caused by the COVID-19 pandemic, which began affecting European societies and economies in 2020*." Structural changes in energy demand and consumption due to COVID-19 have been observed in different demand sectors and peak demand patterns (Jiang, Fan, & Klemeš, 2021). Stakeholders reflected on the effects of the COVID-19 pandemic that caused specific behavioural changes in the context of the energy system. "*Working from home reduced the overall transportation and changed its patterns, while at the same time caused higher demand for gas needed for heating of households*."

RQ94. How do the effects of the home office resulting from the COVID-19 crisis change the current transportation patterns and heat demand?

Where we want to get to

The post-COVID-19 recovery funds amount to €1.8 trillion (European Commission, 2020f). They are currently in the pipeline and could be an ideal opportunity to ensure a fair transition towards carbon neutrality. The Member States should embrace the European Green Deal and the recovery packages to fundamentally transform their energy systems.

How to get there

Stakeholders were interested in the impact that EU recovery packages will have on the energy transition, whether energy poverty will increase during the energy transition, how local communities should be involved, and the socio-economic chances and risks of the energy transition as well as how to include them in the energy models.

RQ95. How would the recovery package affect the European energy transition? How could the recovery funds support prosumer engagement through the involvement of local communities?

Social & consumer acceptance

Where we want to go

Social and consumer acceptance poses an important challenge to electrification and RES development, requiring additional costs or policy changes (Chen et al., 2021). Especially for demand response deployment, consumer acceptance has been regarded as the "*greatest challenge*" (Gjorgievski, Markovska, Abazi, & Duić, 2021). Addressing such challenges demands for high levels of public engagement (Mikova et al., 2019).

How to get there

Active involvement of key stakeholders (i.e., governmental bodies, business, academic community, general public, etc.) may facilitate fruitful discussions and accelerate the citizens' acceptance of new technology pathways (Mikova et al., 2019). Stakeholders argued that "*while the electricity should be balanced according to regionalisation of supply, it may cause conflicts between continental and local interests. Good examples of this include the environmental impacts of small hydro power plants, local wind opposition fuelled by the "not in my back yard" (NIMBY) mentality or concerns related to bioenergy, like the land use and the actual net emissions*."

RQ96. In the context of RES and transmission infrastructure development, how should the local wind power opposition, fuelled by the NIMBY mentality, be dealt with?

RQ97. Which renewable technologies would be the most and least accepted by the European societies?

Energy poverty

Where we want to get to

Prevention of energy poverty through the active role of citizens and communities in the energy transition should be addressed via legal concepts across all EU member states (Inês et al., 2020)."*Issues that could be modelled in the context of the energy transition's affordability could relate to social housing, in which the energy poverty is decreased by increasing efficiency and renovating the buildings*."

RQ98. Would energy poverty decrease during the energy transition? To what extent social housing could contribute to reducing energy poverty? What should be the annual pace of house renovation to reduce energy poverty?

How to get there

Stakeholders indicated that "*for the modelling of a decarbonised energy system it is important to consider both overall negative and positive effects for consumers, which can be reflected, for example, in increasing number of unpaid energy bills*." To avoid that, stakeholders proposed incentives for storage investments, which could harmonise the electricity market and prevent electricity price fluctuation.

RQ99. How can social inequalities resulting from increasing energy and electricity prices be prevented? How many unpaid energy bills will there be each year as a result of the transition towards climate neutrality and how many low-income households should receive electricity for free?

RQ100. What would be the socioeconomic impacts (e.g., change in households' savings and spending, etc.), if energy demand is reduced? How would this influence the member states' budgets?

Sustainable Development Goals (SDGs)

Where we want to get to?

Stakeholders further pointed out a need to investigate the relation between the future European energy system and SDGs.

RQ101. How would the future energy system influence SDGs? What kind of trade-offs exist between a low-carbon energy system and the SDGs?

4. Discussion

With this deliverable we have prepared the playground for the application and testing of the SENTINEL modelling suite in three different case studies. We have identified a reference scenario for each case study, and disruptive energy transition (i.e., climate neutrality) scenarios on a National, Regional and Continental level. These are expected to test the limits of the models regarding their ability to simulate transition pathways dominated by high shares of intermittent renewables, considering diverse spatial scales, and addressing the multifaceted problems of the ongoing energy transition. Furthermore, we have compiled a long list of contextual critical issues and challenges, and specific research questions, clustered according to the relevance outlined by the "Three types of knowledge" tool: **(i).** the context of the energy transition ("*Where we are*"), **(ii).** the energy targets per sector ("*Where we want to get to*"), and **(iii).** the policy tools that will be required to get to the targets ("*How do we get there*").

For the National case study, we find that the main themes related to the power sector are the requirements for secure supply, system flexibility and storage, which stem from the shut-down of lignite-fired power plants, coupled with high penetration of RES. In this context, the role of interconnection capacities in security of supply and system operation, needs to be further investigated. Furthermore, demand electrification with a focus on transport and development of the necessary infrastructure are a critical issue that needs to be further studied. Finally, novel regulatory frameworks to ensure that the post-lignite development trajectory in the coal regions is socially just, need to be explored. This includes also social innovations, relevant to the concept of energy citizenship, such as energy communities, ecovillages, etc.

For the Regional case study, we find that a strengthening of the interconnections with the central European electricity system may be needed, potentially affecting the regional electricity markets. Nuclear energy as a contributor to the future energy system is still a debatable topic and it requires further discussion. The pathway to carbon neutrality will require affordable technologies for negative CO_2 emissions, and the already efficient Nordic industrial sector would need to implement Carbon Capture Storage and/ or Carbon Capture Utilization and Storage technologies and practices. Engagement of the society and other measures are essential to ensure social acceptance for carbon neutrality. The choice of socially accepted or preferred policy instruments and measures, which, at the same time are effective, is a difficult task. In this context, policies facilitating a fair distribution of costs should be given priority. Finally, stakeholders highlighted that it is inaccurate to only consider a unified Nordic energy system, as it is a heterogenic compilation of different national energy systems with concrete characteristics and specificities. Furthermore, it also depends on external processes taking place to other jurisdictions, such as the EU, the Baltic States, or countries supplying particular resources. As a result, a more precise understanding of the different national contexts is needed.

For the Continental case study, we find that different options for flexibility mechanisms should be examined including electricity storage, demand-side flexibility and heat storage, whereas a long-term focus should be given to hydrogen. The degree of decentralisation, should be further investigated, taking into consideration the advances of digitalisation, the degree of electricity self-production, the level of electrification of industry, the possible role of hydrogen in industry, technological locks-in as well as possibilities of power exchange with other areas, like Northern Africa. The projected large reduction of GHG emissions from transport by 2050 requires an investigation of the decarbonisation options and the resulting electricity, and P2X demands. Heat production in manufacturing industries can be proved difficult to decarbonise and should be considered together with efficiency increase options. A major question at the EU level is the distribution of energy transition costs across different sectors and over geographical regions. It is important for Member States to make essential investments in renewable energy technologies and infrastructure while ensuring a socially just transition.

4.1. Common issues and differences

Overall, the questions addressing the System knowledge ("Where we are now") have indicated considerable differences between the existing situation of the energy systems in Greece, in Nordic countries and in Europe. We have seen that the Target knowledge ("Where we want to go") questions show varying degrees of ambition in different scenarios regarding the depth of decarbonisation, and the time-horizon that will be required to achieve this. However, the overall trend is significant emissions reduction targets by 2050 in all cases. Interestingly, there are common themes in Transformation knowledge questions, related to "*How to get*" to the target points, especially in the climate neutrality scenarios.

Important topics regarding the supply side, appearing in all the case studies, are the issues of system flexibility, RES curtailment, and storage. Demand-side flexibility is considered as complementary to supply-side approaches and is further enhanced by sector coupling through extensive electrification of heating and road transport. Differences appear in the electrification of heating pathways since it should utilise the well-established district heating networks of the Nordic countries, while individual use of heat pumps could be the only option in Greece. Electrification of road transport is a target in all the three case studies, although the starting points are rather different, with the Nordic states being the frontrunners, Greece just started deploying the necessary charging infrastructure, and with varying degrees of implementation in the different EU Member States.

In addition, Power-to-X appears as an alternative to direct electrification in the case studies, offering advantages with respect to direct electrification but is subject to uncertainties regarding developments of appropriate technologies and infrastructure. Industry is recognised as the hardest sector to be decarbonised. However, the already efficient Nordic industry is looking towards Carbon Capture Utilization and Storage options, the less heavy industry of Greece might utilise H_2 or electrification to switch away from fossil fuels, while at an EU level, a large combination of options should be further explored. Finally, we have identified the notions of social acceptance for climate neutrality and of just transition as recurring themes in all case studies, and key factors in achieving a zero carbon energy system.

4.2. Limitations of our study and their implications

Stakeholder engagement is at the heart of the work in Work Package 7, but it was severely affected by the coronavirus crisis. It has led to delays and a complete reformulation of the stakeholder engagement activities, compared to our initial planning. Due to social distancing restrictions, the initially planned physical workshops took place online, either as bilateral online meetings or as online workshops. While these activities worked out well, they were very time-intensive, as we invested additional time for adjusting to the new formats and identifying and learning specific online tools that would still allow for an active stakeholder engagement process. In addition, while our overall engagement performance (as presented in **Figure 3**) suggest a sufficient representation of all stakeholder groups, with feedback received from more than 80 stakeholders, it is also apparent that the different stakeholder groups were not equally represented.

More specifically, while our initial mapping and reaching out to stakeholders show an equal proportion between the stakeholder groups, representatives from the policymaking field and NGOs could not be reached with the same ease. Many of them remained either irresponsive or needed additional time to adapt to the new circumstances of the pandemic. Furthermore, it also suggests a different phenomenon that energy modelling remains a highly specific endeavour, which is not equally mainstreamed among all actors active in the energy realm. It confirms that energy modelling traditionally has been a domain either of research institutes or big energy companies and utilities (Pfenninger et al., 2018). Apparently, many of policymakers and representatives of the civil society still do not have sufficient capacities (at least in their own view) to get involved and committed to activities dedicated to energy systems modelling. Nevertheless, we collected a good quality feedback to carry out the work as planned.

Moreover, a general remark from stakeholder engagement activities under both Work Package 1 and Work Package 7 is that the general commitment of invited stakeholders to join online events has been decreasing over time, as people got tired with numerous meetings taking place mostly online for many months. This suggests that we reformulate our approach of engaging stakeholders during the model application part under Task 7.2, and that we explore new engagement tools and formats that could rekindle stakeholders' interest in participating in our events. One solution to that could be the organisation of smaller thematic events, in which SENTINEL modellers could present their modelling results for a range of assumptions, directly to stakeholders. In that case, stakeholders can reflect first-hand on results and share their insights directly with modelling teams. A different idea is to increase the stakeholders' commitment by offering them "something in return". This would mean that we involve specifically selected stakeholders that would be interested in the SENTINEL results, could benefit from the modelling work and use the results in their day-to-day work. That would require even more precisely performed stakeholder mapping exercise, as realised so far.

In addition, in both the cases of the Regional and the Continental case studies, we had to deal with outdated reference scenarios. Especially in the case of the Regional case study, we had to depend on the only scenario available that takes into account the whole Nordic region, which is already rather outdated (Norden & IEA, 2016). As far as we know from the Nordic Energy Research Council representatives, an updated scenario at a regional level will be published soon. A similar situation also concerns the EU Reference scenario, an updated version of which will be published soon. For both cases, we tried to address this limitation by also considering individual countries' updated policy scenarios and targets, based on the most recent version of their Nationally Determined Contributions. However, as soon as the new scenarios are made publicly available, we will make sure to revise and inform case study specifications under our work in Deliverable 7.2.

Finally, we have identified a large number of various research questions, which could serve as a comprehensive reference list for stakeholders, interested in an updated overview on the latest policy developments, the critical issues and challenges of the energy transition in diverge spatial scales, or in the socioeconomic contexts under study. However, we are aware that SENTINEL models will not be able to provide answers to all of these research questions, due to technical and modelling constraints, and to the nature of the questions themselves. The latter concerns especially qualitative questions that refer to social implications, or regulatory specifications and constraints since they are always difficult to quantify using numerical modelling approaches. These limitations will be well-documented during next steps of the work under Work Package 7 (Deliverable 7.2 and Deliverable 7.3) and will be used to highlight new modelling paradigms and trends, as well as priority areas, which energy system models should consider under their scope in the future.

4.3. Outlook: development of participatory transition pathways and qualitative storylines

As next steps, and in cooperation with stakeholders, SENTINEL modellers will calibrate their models to simulate the scenarios presented in this deliverable and provide responses to specific critical issues and challenges. This collaboration will also serve to evaluate the quality of modelling outputs, from a technical standpoint, and in terms of their practical usefulness to stakeholders. In addition, considering the wide range of contextual differences in the three case studies, implementation of the updated models will shed light on issues that remain unsolved, with a goal of their further improvement and achievement of better transparency. Finally, next to serving as the testing ground for the SENTINEL platform, the case studies will provide the basis for a models' intercomparison exercise (Work Package 8). This exercise will aim at identifying the strengths and weaknesses of the different SENTINEL models, both with respect to each other and to other well-established models (e.g., PRIMES, POLES, GEM-E3, Prometheus, POTENCIA, etc.) from outside the consortium. Intercomparison results will be documented under Work Package 8 as a resource for future model users (Roelfsema, Oreggioni, Mikropoulos, Staffell, & Van Vuuren, 2021).

Last, the derived narratives of the potential developments of the energy transition, and technological as well as socioeconomic drivers and challenges, will inform the further development of SENTINEL case study-specific storylines (Task 7.2), underlying the case study scenarios, as well as the development of the QTDIAN social storylines (Deliverable 2.2) and their "translation" in quantitative scenario pathways and model assumptions. The storyline definition in qualitative terms will be further conducted through stakeholders' engagement in the next phases of the project.

References

Abbott, M., & Cohen, B. (2019). Maintaining the security of supply in the Australian national electricity Market with higher levels of renewable energy. *The Electricity Journal*, *32*(9), 106645. https://doi.org/10.1016/j.tej.2019.106645

ACEA. (2018). *Vehicles in use - Europe 2018. European Automobile Manufacturers Association*.

Agora Energiewende. (2015). *The European Power System in 2030 : Flexibility Challenges and Integration Benefits*.

Agora Energiewende and Ember. (2021). *The European Power Sector in 2020: Up-to-Date Analysis on the Electricity Transition*.

Antenucci, A., Crespo, P., Gjorgiev, B., & Sansavini, G. (2019). Can models for long-term decarbonization policies guarantee security of power supply ? A perspective from gas and power sector coupling. *Energy Strategy Reviews*, *26*(October 2018), 100410. https://doi.org/10.1016/j.esr.2019.100410

Attia, S., Eleftheriou, P., Xeni, F., Morlot, R., Ménézo, C., Kostopoulos, V., … Hidalgo-Betanzos, J. M. (2017). Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe. *Energy and Buildings*, *155*(2017), 439–458. https://doi.org/10.1016/j.enbuild.2017.09.043

Bauknecht, D., Funcke, S., & Vogel, M. (2020). Is small beautiful? A framework for assessing decentralised electricity systems. *Renewable and Sustainable Energy Reviews*, *118*(October 2019), 109543. https://doi.org/10.1016/j.rser.2019.109543

Blanco, H., Nijs, W., Ruf, J., & Faaij, A. (2018). Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization. *Applied Energy*, *232*(June), 617–639. https://doi.org/10.1016/j.apenergy.2018.09.216

Bolwig, S., Bolkesjø, T. F., Klitkou, A., Lund, P. D., Bergaentzlé, C., Borch, K., … Skytte, K. (2020). Climate-friendly but socially rejected energy-transition pathways: The integration of techno-economic and socio-technical approaches in the Nordic-Baltic region. *Energy Research and Social Science*, *67*(April), 101559. https://doi.org/10.1016/j.erss.2020.101559

Brown, D., Hall, S., & Davis, M. E. (2019). Prosumers in the post subsidy era: an exploration of new prosumer business models in the UK. *Energy Policy*, *135*(August), 110984. https://doi.org/10.1016/j.enpol.2019.110984

Calderón, C., Underwood, C., Yi, J., Mcloughlin, A., & Williams, B. (2019). An area-based modelling approach for planning heating electrification. *Energy Policy*, *131*(May), 262–280. https://doi.org/10.1016/j.enpol.2019.04.023

Cambini, C., Congiu, R., Jamasb, T., Llorca, M., & Soroush, G. (2020). Energy Systems Integration: Implications for public policy. *Energy Policy*, *143*, 111609. https://doi.org/10.1016/j.enpol.2020.111609

Capros, P., Kannavou, M., Evangelopoulou, S., Petropoulos, A., Siskos, P., Tasios, N., … DeVita, A. (2018). Outlook of the EU energy system up to 2050: The case of scenarios prepared for European Commission's "clean energy for all Europeans" package using the PRIMES model. *Energy Strategy Reviews*. https://doi.org/10.1016/j.esr.2018.06.009

Capros, P., Zazias, G., Evangelopoulou, S., Kannavou, M., Fotiou, T., Siskos, P., … Sakellaris, K. (2019). Energy-system modelling of the EU strategy towards climate-neutrality. *Energy Policy*, *134*(March), 110960. https://doi.org/10.1016/j.enpol.2019.110960

Carlini, E. M., Schroeder, R., Birkebæk, J. M., & Massaro, F. (2019). EU transition in power sector: How RES affects the design and operations of transmission power systems. *Electric Power Systems Research*, *169*(December 2018), 74–91. https://doi.org/10.1016/j.epsr.2018.12.020

Castagneto Gissey, G., Subkhankulova, D., Dodds, P. E., & Barrett, M. (2019). Value of energy storage aggregation to the electricity system. *Energy Policy*, *128*(February), 685–696. https://doi.org/10.1016/j.enpol.2019.01.037

CCC. (2018). Hydrogen in a low-carbon economy Committee on Climate Change Acknowledgements Other members of the Secretariat who contributed to this report, (November), 1–128.

Chen, Y. kuang, Jensen, I. G., Kirkerud, J. G., & Bolkesjø, T. F. (2021). Impact of fossil-free decentralized heating on northern European renewable energy deployment and the power system. *Energy*, *219*, 119576. https://doi.org/10.1016/j.energy.2020.119576

Committee on Climate Change. (2019). Net Zero Technical Report, (May).

Committee on Climate Change. (2020). *Policies for the Sixth Carbon Budget and Net Zero*.

Costello, K. W. (2018). Electrification: The nexus between consumer behavior and public policy. *Electricity Journal*, *31*(1), 1–7. https://doi.org/10.1016/j.tej.2018.01.005

Danish Ministry of Climate, Energy and Utilities. (2019). *Denmark's Integrated National Energy and Climate Plan*.

Dehghani-Sanij, A. R., Tharumalingam, E., Dusseault, M. B., & Fraser, R. (2019). Study of energy storage systems and environmental challenges of batteries. *Renewable and Sustainable Energy Reviews*, *104*(November 2018), 192–208. https://doi.org/10.1016/j.rser.2019.01.023

EEB and CAN Europe. (2020). *A net-zero EU is possible*.

eleftheriaonline.gr. (2019). Πέρασε το ψήφισμα "για να μην κλείσουν οι λιγνιτικές μονάδες της Μεγαλόπολης το 2028" στο Περιφερειακό Συμβούλιο.

Erbach, G. (2019). *Energy storage and sector coupling: Towards an integrated, decarbonised energy system*.

European Commission. (2016). *Reference Scenario 2016. Energy, transport and GHG emissions. Trends to 2050*. Luxembourg.

European Commission. (2018). *A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy*. Brussels.

European Commission. (2019). *The European Green Deal*. https://doi.org/10.1128/AAC.03728-14

European Commission. (2020a). *A New Industrial Strategy for Europe*.

European Commission. (2020b). *A Renovation Wave for Europe – greening our buildings, creating jobs, improving lives*. Brussels.

European Commission. (2020c). *Circular Economy Action Plan. For a cleaner and more competitive Europe*.

European Commission. (2020d). EU Long-Term Strategy.

European Commission. (2020e). *Powering a climate-neutral economy: An EU Strategy for Energy System Integration*. Brussels.

European Commission. (2020f). Recovery plan for Europe.

European Commission. (2020g). Renewable energy directive.

European Commission. (2020h). The Just Transition Mechanism: making sure no one is left behind.

European Parliament. (2020). What is carbon neutrality and how can it be achieved by 2050?

European Parliament and the Council. (2019). Regulation (EU) 2019/943 of 5 June 2019 on the internal market for electricity. *Official Journal of the European Union*.

European Union. (2020). *The update of the nationally determined contribution of the European Union and its Member States*.

Foxon, T. J. (2013). Transition pathways for a UK low carbon electricity future. *Energy Policy*, *52*, 10–24. https://doi.org/10.1016/j.enpol.2012.04.001

Foxon, T. J., Hammond, G. P., & Pearson, P. J. G. (2010). Developing transition pathways for a low carbon electricity system in the UK. *Technological Forecasting and Social Change*, *77*(8), 1203–1213. https://doi.org/10.1016/j.techfore.2010.04.002

Fragkos, P., Laura van Soest, H., Schaeffer, R., Reedman, L., Köberle, A. C., Macaluso, N., … Iyer, G. (2021). Energy system transitions and low-carbon pathways in Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Republic of Korea, Russia and the United States. *Energy*, *216*. https://doi.org/10.1016/j.energy.2020.119385

Fragkos, P., & Paroussos, L. (2018). Employment creation in EU related to renewables expansion. *Applied Energy*, *230*(April), 935–945. https://doi.org/10.1016/j.apenergy.2018.09.032

Gaschnig, H., Süsser, D., Ceglarz, A., Stavrakas, V., Giannakidis, G., Flamos, A., Sander, … Lilliestam, J. (2020). User needs for an energy system modeling platform for the European energy transition. Deliverable 1.2. Sustainable Energy Transitions Laboratory (SENTINEL) project. *European Commission. Institute for Advanced Sustainability Studies (IASS), Potsdam.*

Gianpietro, M., Aspinall, R. J., Ramos-Martin, J., & Bukkens, S. G. F. (2014). *RESOURCE ACCOUNTING FOR SUSTAINABILITY ASSESSMENT*.

Gjorgievski, V. Z., Markovska, N., Abazi, A., & Duić, N. (2021). The potential of power-to-heat demand response to improve the flexibility of the energy system: An empirical review. *Renewable and Sustainable Energy Reviews*, *138*(October 2020). https://doi.org/10.1016/j.rser.2020.110489

Government of Iceland. Ministry for the Environment and the Natural Resources. (2021). *Update of the Nationally Determined Contribution of Iceland*.

Graabak, I., & Korpås, M. (2016). Balancing of Variable Wind and Solar Production in Continental Europe with Nordic Hydropower - A Review of Simulation Studies. *Energy Procedia*, *87*(1876), 91–99. https://doi.org/10.1016/j.egypro.2015.12.362

Graf, A., & Buck, M. (2017). *The cost of renewable energy: A critical assessment of the Impact Assessments underlying the Clean Energy for all Europeans-Package*. Berlin: Agora Energiewende.

Haug, J. K., & Stigson, P. (2016). Local acceptance and communication as crucial elements for realizing CCS in the Nordic region. *Energy Procedia*, *86*(1876), 315–323. https://doi.org/10.1016/j.egypro.2016.01.032

Helin, K., Syri, S., & Zakeri, B. (2018). Improving district heat sustainability and competitiveness with heat pumps in the future Nordic energy system. *Energy Procedia*, *149*, 455–464. https://doi.org/10.1016/j.egypro.2018.08.210

Hellenic Ministry of Environment and Energy. (2020). *Exoikonomo - Aftonomo (In Greek)*.

Höhne, N., de Villafranca, M. J., Nascimento, L., Kuramochi, T., Hans, F., Luna, L., … Warnecke, C. (2019). *A possible 2050 climate target for the EU*. Cologne.

IEA. (2020). “Energy Technology Perspectives 2020.”

Inês, C., Guilherme, P. L., Esther, M. G., Swantje, G., Stephen, H., & Lars, H. (2020). Regulatory challenges and opportunities for collective renewable energy prosumers in the EU. *Energy Policy*, *138*(April 2019). https://doi.org/10.1016/j.enpol.2019.111212

insider.gr. (2019). Αλλάζουν τα δεδομένα στην εθνική ενεργειακή πολιτική - Λουκέτο στις λιγνιτικές μονάδες μέχρι το 2028 (In Greek).

Jäger-Waldau, A., Kougias, I., Taylor, N., & Thiel, C. (2020). How photovoltaics can contribute to GHG emission reductions of 55% in the EU by 2030. *Renewable and Sustainable Energy Reviews*, *126*(March). https://doi.org/10.1016/j.rser.2020.109836

Jiang, P., Fan, Y. Van, & Klemeš, J. J. (2021). Impacts of COVID-19 on energy demand and consumption: Challenges, lessons and emerging opportunities. *Applied Energy*, *285*(November 2020). https://doi.org/10.1016/j.apenergy.2021.116441

Kester, J., Noel, L., Zarazua de Rubens, G., & Sovacool, B. K. (2018a). Policy mechanisms to accelerate electric vehicle adoption: A qualitative review from the Nordic region. *Renewable and Sustainable Energy Reviews*, *94*(September 2017), 719–731. https://doi.org/10.1016/j.rser.2018.05.067

Kester, J., Noel, L., Zarazua de Rubens, G., & Sovacool, B. K. (2018b). Promoting Vehicle to Grid (V2G) in the Nordic region: Expert advice on policy mechanisms for accelerated diffusion. *Energy Policy*, *116*(March), 422–432. https://doi.org/10.1016/j.enpol.2018.02.024

Kjärstad, J., Skagestad, R., Eldrup, N. H., & Johnsson, F. (2016). Ship transport—A low cost and low risk CO2 transport option in the Nordic countries. *International Journal of Greenhouse Gas Control*, *54*, 168–184. https://doi.org/10.1016/j.ijggc.2016.08.024

Korkmaz, P., Gardumi, F., Avgerinopoulos, G., Blesl, M., & Fahl, U. (2020). A comparison of three transformation pathways towards a sustainable European society - An integrated analysis from an energy system perspective. *Energy Strategy Reviews*, *28*, 100461. https://doi.org/10.1016/j.esr.2020.100461

Koumparou, I., Christoforidis, G. C., Efthymiou, V., Papagiannis, G. K., & Georghiou, G. E. (2017). Configuring residential PV net-metering policies – A focus on the Mediterranean region. *Renewable Energy*, *113*, 795–812. https://doi.org/10.1016/j.renene.2017.06.051

Kraan, O., Kramer, G. J., & Nikolic, I. (2018). Investment in the future electricity system - An agent-based modelling approach. *Energy*, *151*, 569–580. https://doi.org/10.1016/j.energy.2018.03.092

Kyritsis, A., Voglitsis, D., Papanikolaou, N., Tselepis, S., Christodoulou, C., Gonos, I., & Kalogirou, S. A. (2017). Evolution of PV systems in Greece and review of applicable solutions for higher penetration levels. *Renewable Energy*, *109*, 487–499. https://doi.org/10.1016/j.renene.2017.03.066

Lennon, B., Dunphy, N., Gaffney, C., Revez, A., Mullally, G., & O’Connor, P. (2020). Citizen or consumer? Reconsidering energy citizenship. *Journal of Environmental Policy and Planning*, *22*(2), 184–197. https://doi.org/10.1080/1523908X.2019.1680277

Liebensteiner, M., & Wrienz, M. (2019). Do Intermittent Renewables Threaten the Electricity Supply Security? *Energy Economics*, 104499. https://doi.org/10.1016/j.eneco.2019.104499

Magrini, A., Lentini, G., Cuman, S., Bodrato, A., & Marenco, L. (2020). From nearly zero energy buildings (NZEB) to positive energy buildings (PEB): The next challenge - The most recent European trends with some notes on the energy analysis of a forerunner PEB example. *Developments in the Built Environment*, *3*(March), 100019. https://doi.org/10.1016/j.dibe.2020.100019

Mata Pérez, M. de la E., Scholten, D., & Smith Stegen, K. (2019). The multi-speed energy transition in Europe: Opportunities and challenges for EU energy security. *Energy Strategy Reviews*, *26*(December 2018). https://doi.org/10.1016/j.esr.2019.100415

Material Economics. (2019). *Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry*. *Report*.

McKenna, R. (2018). The double-edged sword of decentralized energy autonomy. *Energy Policy*, *113*(May 2017), 747–750. https://doi.org/10.1016/j.enpol.2017.11.033

Merk, C., Rehdanz, K., & Schröder, C. (2019). How consumers trade off supply security and green electricity: Evidence from Germany and Great Britain. *Energy Economics*, *84*, 104528. https://doi.org/10.1016/j.eneco.2019.104528

Michas, S., Stavrakas, V., Spyridaki, N., & Flamos, A. (2019). Identifying Research Priorities for the further development and deployment of Solar Photovoltaics. *International Journal of Sustainable Energy*, (38:3), 276–296. https://doi.org/10.1080/14786451.2018.1495207

Mikova, N., Eichhammer, W., & Pfluger, B. (2019). Low-carbon energy scenarios 2050 in north-west European countries: Towards a more harmonised approach to achieve the EU targets. *Energy Policy*, *130*(May), 448–460. https://doi.org/10.1016/j.enpol.2019.03.047

Mikulčić, H., Baleta, J., Klemeš, J. J., & Wang, X. (2021). Energy transition and the role of system integration of the energy, water and environmental systems. *Journal of Cleaner Production*, *292*. https://doi.org/10.1016/j.jclepro.2021.126027

Ministry of Economic Affairs and Employment. (2019). *Finland's Integrated Energy and Climate Plan*.

Ministry of Environment and Energy. (2019a). *Long Term Strategy for 2050 (In Greek)*.

Ministry of Environment and Energy. (2019b). *National Energy and Climate Plan: Greece*.

Mustapha, W. F., Kirkerud, J. G., Bolkesjø, T. F., & Trømborg, E. (2019). Large-scale forest-based biofuels production: Impacts on the Nordic energy sector. *Energy Conversion and Management*, *187*(March), 93–102. https://doi.org/10.1016/j.enconman.2019.03.016

Nanaki, E. A., & Xydis, G. A. (2018). Deployment of Renewable Energy Systems: Barriers, Challenges, and Opportunities. *Advances in Renewable Energies and Power Technologies*, *2*, 207–229. https://doi.org/10.1016/B978-0-12-813185-5.00005-X

Network for Transdisciplinarity Research. (2021). Three types of knowledge tool A tool for tailoring research questions to (societal) knowledge demands. Retrieved February 26, 2021, from https://naturalsciences.ch/co-producing-knowledge-explained/methods/td-net_toolbox/three_types_of_knowledge_tool

Nikas, A., Neofytou, H., Karamaneas, A., Koasidis, K., & Psarras, J. (2020). Sustainable and socially just transition to a post-lignite era in Greece: a multi-level perspective. *Energy Sources, Part B: Economics, Planning, and Policy*. https://doi.org/10.1080/15567249.2020.1769773

Nikas, A., Stavrakas, V., Arsenopoulos, A., Doukas, H., Antosiewicz, M., Witajewski-Baltvilks, J., & Flamos, A. (2019). Barriers to and consequences of a solar-based energy transition in Greece. *Environmental Innovation and Societal Transitions*. https://doi.org/10.1016/j.eist.2018.12.004

Norden & IEA. (2016). *Nordic Energy Technology Perspectives 2016. Cities, flexibility and pathways to carbon-neutrality*. Paris. https://doi.org/10.1787/9789264257665-en

Nordic Co-operation. (2019). "Stepping up Nordic climate co-operation."

Nordic Energy Research. (2019). Tracking Nordic Clean Energy Progress 2019, (October).

Nordic Energy Research. (2020). Tracking Nordic Clean Energy Progress 2020, (April), 30.

Nordic, T., Panel, I., Change, C., Report, S., Warming, G., Agreement, P., … Reform, S. (2020). Declaration on Nordic Carbon Neutrality.

Norwegian Ministry of Climate and Environment. (2019). *Norway's National Plan. related to the Decision of the EEA Joint Committee*.

Norwegian Ministry of Climate and Environment. (2020). *Update of Norway's nationally determined contribution*.

Nycander, E., Söder, L., Olauson, J., & Eriksson, R. (2020). Curtailment analysis for the Nordic power system considering transmission capacity, inertia limits and generation flexibility. *Renewable Energy*, *152*, 942–960. https://doi.org/10.1016/j.renene.2020.01.059

Oberthür, S. (2011). The European Union's Performance in the International Climate Change Regime. *Journal of European Integration*, *33*(6), 667–682. https://doi.org/10.1080/07036337.2011.606690

Olczak, M., & Piebalgs, A. (2018). Sector Coupling: the New EU Climate and Energy Paradigm? *Florence Schol of Regulation*, (2018/17), 12.

Olkkonen, V., & Syri, S. (2016). Spatial and temporal variations of marginal electricity generation: The case of the Finnish, Nordic, and European energy systems up to 2030. *Journal of Cleaner Production*, *126*, 515–525. https://doi.org/10.1016/j.jclepro.2016.03.112

Ollila, J. (2017). *Nordic Energy Cooperation: Strong today- stronger tomorrow*. Nordic Council of Ministers: Copenhagen.

Paci, S., Bertoldi, D., & Shnapp, S. (2020). *Enabling Positive Energy Districts across Europe : energy efficiency couples renewable energy*. https://doi.org/10.2760/452028

Pereirinha, P. G., González, M., Carrilero, I., Anseán, D., Alonso, J., & Viera, J. C. (2018). Main Trends and Challenges in Road Transportation Electrification. *Transportation Research Procedia*, *33*, 235–242. https://doi.org/10.1016/j.trpro.2018.10.096

Perellis, A, Mezartasoglou, D., & Stambolis, C. (2018). Anticipated Penetration Rate of Electric Vehicles in Greece ' s Motor Vehicle Market. In *3rd HAEE Energy Conference: "Energy Transition: European and Global Perspectives."*

Perellis, Alexandros, & Stambolis, C. (2018). *IENE Working Paper No24: Prospects for the Electric Vehicle Market and Business opportunities with special reference to SE Europe and Greece*.

Pfenninger, S., Hirth, L., Schlecht, I., Schmid, E., Wiese, F., Brown, T., … Wingenbach, C. (2018). Opening the black box of energy modelling: Strategies and lessons learned. *Energy Strategy Reviews*, *19*, 63–71. https://doi.org/10.1016/j.esr.2017.12.002

Pimm, A. J., Cockerill, T. T., & Taylor, P. G. (2018). The potential for peak shaving on low voltage distribution networks using electricity storage. *Journal of Energy Storage*, *16*, 231–242. https://doi.org/10.1016/j.est.2018.02.002

Pleßmann, G., & Blechinger, P. (2017). How to meet EU GHG emission reduction targets? A model based decarbonization pathway for Europe's electricity supply system until 2050. *Energy Strategy Reviews*, *15*, 19–32. https://doi.org/10.1016/j.esr.2016.11.003

Psomas, S. (2019). New business models in the PV market (In Greek). In *Renewable & Storage Forum*.

Pursiheimo, E., Holttinen, H., & Koljonen, T. (2017). Path toward 100% renewable energy future and feasibility of power-to-gas technology in Nordic countries. *IET Renewable Power Generation*, *11*(13), 1695–1706. https://doi.org/10.1049/iet-rpg.2017.0021

Rodríguez-Huerta, E., Rosas-Casals, M., & Sorman, A. H. (2017). A societal metabolism approach to job creation and renewable energy transitions in Catalonia. *Energy Policy*, *108*(June), 551–564. https://doi.org/10.1016/j.enpol.2017.06.024

Roelfsema, M., Oreggioni, G., Mikropoulos, S., Staffell, I., & Van Vuuren, D. . (2021). SENTINEL Intercomparison protocol. Deliverable 8.1, Sustainable Energy Transitions Laboratory (SENTINEL) project, Utrecht: Utrecht University (UU).

Ruhnau, O., Bannik, S., Otten, S., Praktiknjo, A., & Robinius, M. (2019). Direct or indirect electrification? A review of heat generation and road transport decarbonisation scenarios for Germany 2050. *Energy*, *166*, 989–999. https://doi.org/10.1016/j.energy.2018.10.114

Rydén, M., Lyngfelt, A., Langørgen, O., Larring, Y., Brink, A., Teir, S., … Karmhagen, P. (2017). Negative CO2 Emissions with Chemical-Looping Combustion of Biomass - A Nordic Energy Research Flagship Project. *Energy Procedia*, *114*(November 2016), 6074–6082. https://doi.org/10.1016/j.egypro.2017.03.1744

Shivakumar, A., Dobbins, A., Fahl, U., & Singh, A. (2019). Drivers of renewable energy deployment in the EU: An analysis of past trends and projections. *Energy Strategy Reviews*, *26*(September), 100402. https://doi.org/10.1016/j.esr.2019.100402

Shivakumar, A., Pye, S., Anjo, J., Miller, M., Rouelle, P. B., Densing, M., & Kober, T. (2018). Smart energy solutions in the EU: State of play and measuring progress. *Energy Strategy Reviews*, *20*, 133–149. https://doi.org/10.1016/j.esr.2018.02.005

Solomon, A. A., Bogdanov, D., & Breyer, C. (2019). Curtailment-storage-penetration nexus in the energy transition. *Applied Energy*, *235*(May 2018), 1351–1368. https://doi.org/10.1016/j.apenergy.2018.11.069

Song, J., Oh, S. D., Yoo, Y., Seo, S. H., Paek, I., Song, Y., & Song, S. J. (2018). System design and policy suggestion for reducing electricity curtailment in renewable power systems for remote islands. *Applied Energy*, *225*(January), 195–208. https://doi.org/10.1016/j.apenergy.2018.04.131

Sovacool, B. K., Kester, J., de Rubens, G. Z., & Noel, L. (2018). Expert perceptions of low-carbon transitions: Investigating the challenges of electricity decarbonisation in the Nordic region. *Energy*, *148*, 1162–1172. https://doi.org/10.1016/j.energy.2018.01.151

Spodniak, P., Ollikka, K., & Honkapuro, S. (2021). The impact of wind power and electricity demand on the relevance of different short-term electricity markets: The Nordic case. *Applied Energy*, *283*(October 2020), 116063. https://doi.org/10.1016/j.apenergy.2020.116063

Spyridaki, N. A., Stavrakas, V., Dendramis, Y., & Flamos, A. (2020). Understanding technology ownership to reveal adoption trends for energy efficiency measures in the Greek residential sector. *Energy Policy*, *140*. https://doi.org/10.1016/j.enpol.2020.111413

Statnet, Energinet.dk, Svenska Kraftnat, & Fingrid. (2016). *Challenges and Opportunities for the Nordic Power System*.

Stavrakas, V., Spyridaki, N.-A., & Flamos, A. (2018). Striving towards the deployment of bio-energy with carbon capture and storage (BECCS): A review of research priorities and assessment needs. *Sustainability (Switzerland)*, *10*(7). https://doi.org/10.3390/su10072206

Stavrakas, Vassilis, & Flamos, A. (2020). A modular high-resolution demand-side management model to quantify benefits of demand-flexibility in the residential sector. *Energy Conversion and Management*, *205*. https://doi.org/10.1016/j.enconman.2019.112339

Stavrakas, Vassilis, Kleanthis, N., & Flamos, A. (2020). An Ex-Post Assessment of RES-E Support in Greece by Investigating the Monetary Flows and the Causal Relationships in the Electricity Market. *Energies*, *13*(17), 4575. Retrieved from https://doi.org/10.3390/en13174575

Stavrakas, Vassilis, Papadelis, S., & Flamos, A. (2019). An agent-based model to simulate technology adoption quantifying behavioural uncertainty of consumers. *Applied Energy*, *255*, 113795. https://doi.org/10.1016/j.apenergy.2019.113795

Strapasson, A., Woods, J., Meessen, J., Mwabonje, O., Baudry, G., & Mbuk, K. (2020). EU land use futures: modelling food, bioenergy and carbon dynamics. *Energy Strategy Reviews*, *31*(April), 100545. https://doi.org/10.1016/j.esr.2020.100545

Süsser, D., Ceglarz, A., Gaschnig, H., Stavrakas, V., Flamos, A., & Giannakidis, G. Lilliestam, J. (n.d.). Model-based policymaking or policy-based modelling? How energy models and energy policy interact. *Energy Research & Social Science*, *In press*.

Süsser, D., Ceglarz, A., Gaschnig, H., Stavrakas, V., Giannakidis, G., Flamos, A., … Liliestam, J. (2020). *The use of energy modelling results for policymaking in the EU, Deliverable 1.1, SENTINEL*.

Süsser, D., Gaschnig, H., Ceglarz, A., Stavrakas, V., Flamos, A., & Lilliestam, J. (n.d.). Better suited or just more complex? On the fit between user needs and modeller-driven improvements of energy system models. *Energy*, *In review*.

Swain, R. B., & Karimu, A. (2020). Renewable electricity and sustainable development goals in the EU. *World Development*, *125*, 104693. https://doi.org/10.1016/j.worlddev.2019.104693

Swiss Federal Office for the Environment (SFOEN). (2020). *Switzerland's updated and enhanced nationally determined contribution (NDC) under the Paris Agreement (2021– 2030)*.

Szabó, L., Kelemen, Á., Mezősi, A., Pató, Z., Kácsor, E., Resch, G., & Liebmann, L. (2019). South East Europe electricity roadmap–modelling energy transition in the electricity sectors. *Climate Policy*, *19*(4), 495–510. https://doi.org/10.1080/14693062.2018.1532390

Tenggren, S., Wangel, J., Nilsson, M., & Nykvist, B. (2016). Transmission transitions: Barriers, drivers, and institutional governance implications of Nordic transmission grid development. *Energy Research and Social Science*, *19*, 148–157. https://doi.org/10.1016/j.erss.2016.06.004

The Ministry of Infrastructure. (2020). *Sweden's Integrated National Energy and Climate Plan*.

Thomaßen, G., Kavvadias, K., & Jiménez Navarro, J. P. (2021). The decarbonisation of the EU heating sector through electrification: A parametric analysis. *Energy Policy*, *148*(August 2020). https://doi.org/10.1016/j.enpol.2020.111929

Tröndle, T., Pfenninger, S., & Lilliestam, J. (2019). Home-made or imported: On the possibility for renewable electricity autarky on all scales in Europe. *Energy Strategy Reviews*, *26*(August 2018), 100388. https://doi.org/10.1016/j.esr.2019.100388

Tuszyńska, B. (2018). *Transport and Tourism in Greece*.

Uche-Soria, M., & Rodríguez-Monroy, C. (2020). Energy planning and its relationship to energy poverty in decision making. A first approach for the Canary Islands. *Energy Policy*, *140*(August 2019), 111423.

https://doi.org/10.1016/j.enpol.2020.111423

UK Government. (2020). *United Kingdom of Great Britain and Northern Ireland's Nationally Determined Contribution*.

Welsch, M., Howells, M., Hesamzadeh, M. R., Ó Gallachóir, B., Deane, P., Strachan, N., … Rogner, H. (2014). Supporting security and adequacy in future energy systems: The need to enhance long-term energy system models to better treat issues related to variability. *Internal Journal of Energy Research*, *39*, 377–396. https://doi.org/10.1002/er.3250

Wendling, Z. A. (2019). Energy Research & Social Science Bridges beyond renewable energy : Decarbonizing the global electricity sector under uncertainty. *Energy Research & Social Science*, *48*(September 2018), 235–245. https://doi.org/10.1016/j.erss.2018.09.020

Wurzel, R. K. W., Connelly, J., & Liefferink, D. (2016). *The European Union in International Climate Change Politics. Still Taking a Lead?* London and New York: Routledge.

Xu, J., & Liu, T. (2020). Technological paradigm-based approaches towards challenges and policy shifts for sustainable wind energy development. *Energy Policy*, *142*(April). https://doi.org/10.1016/j.enpol.2020.111538

Yin, S., Wang, J., & Qiu, F. (2019). Decentralized electricity market with transactive energy – A path forward. *Electricity Journal*, *32*(4), 7–13. https://doi.org/10.1016/j.tej.2019.03.005

Yu, B., Fang, D., & Dong, F. (2020). Study on the evolution of thermal power generation and its nexus with economic growth: Evidence from EU regions. *Energy*, *205*, 118053. https://doi.org/10.1016/j.energy.2020.118053

Appendix

Section A. National case study background information

A1. Agenda of the National level case study workshop that was cancelled

NATIONAL WORKSHOP

"Scenarios of energy transition in Greece towards 2030 & 2050: Challenges, uncertainties, solutions"

7 April 2020

Venue: "Electra Palace Athens" Hotel 18- 20, N. Nikodimou Str., 10557 Athens, Greece,
Conference Room "Alkyoni"

The recent National Energy and Climate Plan (NECP) is the new framework, within which Greece sets out, in an **integrated** manner, the country's **climate** and **energy** objectives, targets, policies and measures, for the upcoming decade, also considering the European Union' relevant targets for **2030**, and UNDP's **Sustainable Development Goals** (SDGs). Referring to the year 2030, the recently updated long-term plan for the Greek energy system (**Energy Roadmap 2050**) serves in a complementary way to the NECP, and highlights the range of the **available solutions** and **different scenarios** for the upcoming energy transition, in the context of the **long-term** European energy strategy for 2050. Both plans set fair and ambitious goals.

*However, is "**climate-neutrality of 1.5°C**", as promoted by both plans, a **feasible** choice after all, maintaining the **modernization** and **competitiveness** of the national **economy** as key components, and creating an environment of **social justice** without **'winners and losers'** for an energy transition with "**no one being left behind**"?*

This Roundtable Workshop aims at bringing together representatives and stakeholders from all important institutions to highlight critical issues of the country's energy transition towards 2030 and 2050. In particular, stakeholders from the electricity and gas markets, RES and energy efficiency institutions, along with policymakers from the Ministry of Environment and Energy (MEE), will participate in a one-day meeting to exchange diverge views on:

- the critical issues for the Greek energy transition in all sectors, considering the country's commitment to **phase out lignite** by **2028**,
- **challenges** towards the achievement of the ambitious **2050** targets,
- potential implementation **risks**, and ways to mitigate them, to ensure the **smooth** evolution of the national energy system.

09.00 - 09.30	**Registration- Coffee**

09.30 - 10.00	**Welcome- Opening**
09.30 - 09.45 09.45 - 10.00	Welcome remarks- "Tour de table" Opening statement: "Introduction to the SENTINEL project and the Greek case study"
10.00 - 11.15	**Session I: "New electricity market design, RES business models and the role of storage systems: Obligations, uncertainties and pursuits"**
	One of the main priorities of the national energy planning is the goal for phasing out all lignite-fired power plants by 2028, an objective which is at the heart of the European Green Deal, and in line with the EU's commitment to global climate action under the Paris Agreement and climate neutrality by 2050. In the context of the EU Target Model, foreseeing sector coupling and the development of a single electricity market in Europe, the focal point of the national energy transition is the formulation of a new electricity mix that will be based on the integration of high shares of RES. In order for this transition to happen in a fair and socially just manner, with "no one being left behind", it is important to create a secure environment for investments, leveraging public and private funds, establish a sustainable spatial planning for RES installations in an environment-friendly way, and formulate an integrated, fully-interconnected and well-functioning electricity market that offers competitive and transparent prices for products and services to consumers. Finally, for the integration of high shares of variable RES, it is important to ensure that the regulatory environment adapts to the deployment of storage units in the new electricity market. **Roundtable discussion with key stakeholders** Indicative Key Questions: – *How will the decommissioned lignite-fueled fired plants, and the added RES capacity affect the system marginal price and the total system cost?* – *What is the expected RES adoption rate under different business models? Do novel business models (e.g., leasing, sale, and lease back) attract vulnerable (risk-averse) consumers' investment interest?* – *What should be the market rules for the participation of RES in the new market to avoid profiteering and ensure equity among generating technologies?* – *How does the resulting electricity mix affect the LCOE under different RES business models and what are the implications for vulnerable consumers? Which RES adoption rates should be followed to avoid negative consumer price impact?* – *How much RES capacity and storage is needed to reach a 100% renewable energy electricity mix without excessive curtailment? How does RES capacity relate to RES generation and storage needs? What is the cost of each additional percent of RES generation injected to the system?* – *How are the average emissions of the Greek electricity system expected to evolve when many RES are deployed under high-RES penetration, and reduced contribution from conventional generating units?*
11.15 - 11.30	**Coffee break**
11.30 - 12.45	**Session II: "Opportunities for end-use sector coupling through RES deployment, and solutions towards energy security"**
	End-use sector coupling can facilitate increased deployment of intermittent RES, and cross-vector integration between electricity, gas and heat can serve as an additional source of energy system flexibility and security of energy supply. In this context, and since RES are most cost-competitive in electricity generation and have significant potential, electrification is considered as a cost-effective way to decarbonize energy demand. To this end, at the heart of the national energy planning lies the potential for electrification of end-use sectors as heating and transport. In particular, the gradual electrification of the transport sector, with a significant penetration of electric vehicles (EVs), is the most significant challenge for the next decade, especially during the period 2028-2030, when the integration of high shares of RES, along with the use of advanced biofuels are anticipated. Furthermore, the energy consumption for heating is an area where end-use sector coupling through heat pumps is anticipated to play a crucial role, with electric boilers also participating with an increased share. The role of biomass as a heating source is expected to remain the same, while geothermal energy is expected to contribute to a lesser extent to the final mix. In addition, it seems that the role of natural gas, serving as a transitioning alternative to carbon-neutral gases in crucial.

	Finally, the expected electricity consumption profiles as a result of promoting sector coupling, along with less carbon-intensive sources of electricity, call for a system reformulation so that the security and reliability of energy supply is secured, and the country’s import dependency, which is currently at very high levels, is reduced. In this context, system operators face a number of ongoing challenges, as RES generally require a higher degree of flexibility from the network to compensate for their intermittency. **Roundtable discussion with key stakeholders** Indicative Key Questions: – *How can we properly account for capacity adequacy and security of power supply when planning long-term transition pathways based on end-use sector coupling? Do the existing models address these issues?* – *Can natural gas-fired generation units contribute to meeting the demand and system reserve requirements when large RES penetration occurs?* – *How would the electrification of the end-use affect the electricity mix? Are there increased needs for reserves and what is the role of imports due to the increased demand? What are the expected effects on electricity prices?*
13.45 - 14.00	**Session III: “Energy efficiency, decentralization and digitalization: Technology and policy innovative solutions”**
	In the context of securing energy supply, and addressing spatial challenges emerging due to the integration of high shares of RES, the role of energy efficiency and energy conservation is decisive. With regards to this aspect, the NECP foresees very ambitious targets, highlighting the needs for energy efficiency improvements in all aspects of end-use, and eliminating energy poverty. Additionally, important role in the upcoming energy transition will also play the promotion of small-scale RES systems in the building sector, through the further support of market-based schemes (e.g., net-metering), along with a structured policy framework that supports the introduction of demand-side management measures. Such schemes intend to further support RES investments in a decentralized level, and raise public awareness on the dependence of energy consumption to individual behavior, motivating people to regulate their energy consumption as a way to benefit financially from obtaining energy saving practices. As a result, residential end-users will be encouraged to play a more active role in the management of electric power supply and demand, and they are expected to shift from passive consumers to active co-suppliers called prosumers. In this context, the role of the digitalization of end-use through the promotion of novel information and communication technologies (ICTs), is a prerequisite for the proper functioning of the energy system, focusing also on safely managing personal data of consumers. **Roundtable discussion with key stakeholders** Indicative Key Questions: – *Can energy conservation in the building sector reduce the need for costly storage installations? How can current regulatory barriers hindering RES deployment in Zero Emission Buildings (ZEB) be resolved?* – *Which business models could incentivize prosumers to invest in RES projects? What are the benefits of prosumers under different net-metering and/or self-consumption schemes? Which business models (e.g., leasing) could be applied to reduce high initial investment costs, especially in the case of energy poor households?* – *Can distributed RES systems and community scale virtual power plants achieve electricity independency? Which criteria should they fulfil in order to become energy-autonomous? What is the ‘optimum degree of decentralization’ for the Greek electricity system considering non-interconnected islands?*
14.00 - 14.10	**Closing remarks - Farewell**
14.10 - 15.30	**Family photo & Lunch buffet**

Participating institutions and stakeholders:

Ministry of Environment and Energy (MEE)
Public Power Corporation S.A. (PPC S.A.)
Public Gas Company S.A. (DEPA S.A.)
Hellenic Electricity Distribution Network Operator (HEDNO)
Independent Power Transmission Operator (IPTO)
Regulatory Authority for Energy (RAE)
Hellenic Gas Transmission System Operator S.A. (DESFA S.A.)
Hellenic Energy Exchange S.A. (HEnEx S.A.)
Technical Chamber of Greece (TEE - TCG)
Hellenic Association of Independent Power Producers (haipp)
Hellenic Petroleum Marketing Companies Associatio (SEEPE)
Hellenic Association of Renewable Energy Sources Power Producers (hellasres)
Hellenic Wind Energy Association (HWEA/ELEATEN)
Hellenic Association of Photovoltaic Companies (HELAPCO)
Hellenic Small Hydropower Association (HSHA)
Center for Renewable Energy Sources (CRES)
Institute of Zero Energy Buildings (INZEB)
Independent Energy Consultants

SENTINEL at a glance

SENTINEL
SUSTAINABLE ENERGY TRANSITIONS

DURATION: July 2019- May 2022
FUNDING PROGRAMME: EU Horizon 2020 Research and Innovation programme under grant agreement No. 837089
WEBSITE: https://sentinel.energy/
CONTACT: contact@sentinel.energy

The transition to a **low-carbon energy system**, as understood by the scientific and policy communities, will involve a major **redesign** of the energy system, primarily around renewable sources, in accordance with **2030** and **2050** targets that the European Commission has defined. The **SENTINEL** project is aligned with the Energy Union strategy and the EU's commitment under the **Paris Agreement**, which implies the necessity of **accelerating** the energy transition, ultimately leading to the **complete elimination** of energy sector greenhouse gas emissions. At the core of the funding call is the recognition that accelerating this transition requires us to develop a **new** set of energy **modelling tools**, able to represent and analyse the **drivers** and **barriers** to complete decarbonisation, including **decentralisation**, a **large-scale expansion** of fluctuating renewable power leading to a vastly increased need for **system-side flexibility**, **sector coupling** including the electrification of mobility and heating, and the impacts of different **market designs** on the behaviour of energy sector actors.

We are creating a new modelling framework, which we call the **Sustainable Energy Transitions Laboratory** (SENTINEL). The SENTINEL framework will be **modular** in structure incorporating many separate models which will look in detail at specific **technological**, **geographic**, and **societal** aspects of the transition to a low-carbon energy system. The models will be able to be **linked** together to answer a wide range of different questions. For a given **user** in a given **situation**, only a subset of the models are likely to be needed, and this will make it a manageable task to understand how those particular models operate. The **models** in the framework, together with the **data** on which they rely, will be **accessible** via an online platform. The platform will also make available the model **source code** and data, together with supporting **documentation** and **guidance**. This will achieve complete **transparency**, and also enable **other** models to be added to the SENTINEL framework and online platform over time. The project is now officially underway with partners working to pool their modelling expertise with the eventual aim of creating **Sentinel's online platform**.

Extensive **collaboration** with **stakeholders** will inform the development and refinement of the SENTINEL framework. First, we will learn from key stakeholders what **functionality** they need. Second, we will apply the framework to address a set of **case studies**, to address specific problems that policy- and decision-makers will face in the next three years. They will help us **evaluate** how well the framework meets their **needs**, in order to improve it further.

Finally, we will **disseminate** our results and **promote** the platform to the appropriate target **audiences**: **policy**-analysts; model **developers**; and **research** scientists. In addition, we will organise a set of **conferences**, in which we help to build a **community** of model users and developers to carry this work forward. Keep an eye on the website for further details: Your involvement and ideas are key in guiding the project objectives and we look forward to **working with you**!

Meet the partners!

No	Participant organisation name	Country
1 (Coordinator)	Swiss Federal Institute of Technology ***(ETH Zurich)***	CH
2	University of Aalborg ***(AAU)***	DK
3	Central European University ***(CEU)***	HU
4	Hertie School of Governance ***(HSOG)***	DE
5	Imperial College of Science, Technology and Medicine ***(Imperial)***	UK
6	University of Utrecht ***(UU)***	NL
7	Public Power Corporation ***(PPC)***	GR
8	Renewables Grid Initiative ***(RGI)***	DE
9	Autonomous University of Barcelona ***(AUB)***	ES
10	University of Graz ***(UniGraz)***	AT
11	Technoeconomics of Energy Systems laboratory, University of Piraeus Research Centre ***(TEESlab-UPRC)***	GR
12	Institute for Advanced Sustainability Studies ***(IASS)***	DE

Section B. Regional case study background information

B1. Agenda of the Regional level case study workshop

PERSONAL INVITATION AND SAVE-THE-DATE FOR THE ONLINE WORKSHOP

"The Nordic Region- a frontrunner of the decarbonised energy system"

DATE: 4 November 2020
TIME: 10.00- 13.15 CET
JOIN: Zoom link

The EU Horizon 2020 project SENTINEL develops, tests, and makes freely available a modelling framework that will **allow a wide range of energy stakeholders to address the critical energy design challenges** they confront. To make sure that the framework meets the needs of stakeholders, we invite **energy decision-makers from politics, business, and civil society** as well as **energy modellers** to our online workshop that focuses on the Nordic region and its pathway to climate neutrality.

Five Nordic countries are pursuing a common, ambitious vision of a climate neutral region. In order to meet this objective, energy models can function as important support tools towards the clean energy system by 2050. In this regard, the Nordic Energy Research Council (NERC) publishes an annual report that tracks to assess the transition progress, making detailed scenario-based analysis with specialised modelling tools. While the results themselves holistically present the Nordic pathway to carbon neutrality, it is not clear whether the tools used to model them answer all relevant questions of stakeholders interested in the Nordic future energy system.

Our workshop provides you with the **opportunity to share your perspectives on what kind of questions the SENTINEL modelling framework should be able to answer** in the Nordic context. Through the participation in the workshop, you will (1) actively **define the research agenda for new and improved energy models that fit your purpose**, (2) **gain first-hand insights** on major computer-based energy modelling tools, (3) **meet and network** with the model developers and relevant stakeholders from policymaking, energy industry, and civil society, and (4) indirectly **impact policy advice** in the energy field for the European Commission as well as for the Nordic Council of Ministers.

AGENDA

10.00-10.30: Welcome

In the welcoming session, we put the objectives of this workshop in the context of the SENTINEL project. We will discuss the proceeding of the event and collect insights from the participants about their expectations.

Parallel thematic sessions: Your questions to be answered by the models

In virtual break-out groups, we look deeper into the essential aspects of the energy system in order to discuss their future challenges, transition needs, and opportunities, which should be addressed by the energy models. Different SENTINEL modelling teams will host these parallel sessions and collect your input. Closer to the workshop, we will send you a request to sign up for the sessions of your choice!

10.30-11.20: Defining your needs regarding the models– Round I

Session 1: Transforming the power sector
The Nordic power sector is already close to be decarbonised with promising prospects to integrate more wind power and to serve as an electricity hub for the rest of Europe, including electricity export as well as balancing European variable renewables.

Session 2: Sector coupling- implementing smart energy systems and P2X solutions
While electrification of transport and heat supply are important measures to switch both sectors into renewables, with well-established district heating grids in the Nordic countries, implementation of P2X solutions and smart energy systems (e.g., ability to use waste heat from electrolysers) will bring the sector coupling to a higher level of modelling complexity.

Session 3: Decarbonisation of industry and carbon capture and storage
While the Nordic industrial sector is already energy- and material efficient, further improvements will require technological innovation, including substantial application of carbon capture and storage and utilisation (CCS and CCU).

Session 4: Energy Efficiency & smart buildings
Since the Nordic urban areas are expected to grow at twice the rate of previous decades, this implies an application of various measures to improve energy efficiency of the buildings.

Session 5: Environmental impacts and implications
The application of different technologies leading to a decarbonised energy system will mean differentiated environmental impacts, related e.g., to use of recourses or space.

Session 6: Socio-economic aspects and implications
The way to a decarbonised energy system should remain socially sustainable, ensuring a just participation of all members of the society, as well as guaranteeing a fair distribution of costs and benefits.

11.20- 11.40: Coffee break

11.40- 12.30: Defining your needs regarding the models– Round II
In order to provide the possibility to express your views on more than one aspect of the future Nordic energy system, you will be able to join a different thematic session in the second round of virtual break-out groups, where we reshuffle the participants to provide fruitful and multifaceted discussions.

12.30- 13.15: Plenary session
In the plenary, moderators of each thematic session will share the insights of their sessions regarding future challenges and needs, which should be addressed by the energy models with the rest of the participants. Here, you will also have the possibility to comment on the outcomes of the break-out groups, in which you did not participate. At the end of the workshop, we will present and explain how we will utilise the outcomes of the workshop as well as how you can get involved at later stages of SENTINEL.

Section C. Continental case study background information

C1. Agenda of the Continental level case study workshop

PERSONAL INVITATION AND SAVE-THE-DATE FOR THE ONLINE WORKSHOP

"The future of the European energy system: Unveiling the blueprint towards a climate-neutral economy"

DATE: 9 December 2020
TIME: 09.30- 13.10 CET
JOIN: Zoom link

The EU Horizon 2020 project SENTINEL develops, tests, and makes freely available a modelling framework that will **allow a wide range of energy stakeholders to address the critical energy design challenges**. To make sure that the framework meets the needs of stakeholders, we invite **energy decision-makers from politics, business, and civil society** as well as **energy modellers** to our online workshop that focuses on the European Union and its pathway to climate neutrality.

The European Union has always been a leader in fighting climate change through ambitious policies. The current vision of becoming the world's first climate-neutral continent by 2050 is the latest in a series of steps, which will lead to the complete transformation of the current energy system. The European Green Deal with the ambitious measures for GHG reduction, pushing investments in research and innovation, is expected to accelerate this transformation. Energy system modelling has been in the heart of future climate scenarios, but the new policies require better adapted tools for addressing energy transition and its uncertainties.

Our workshop provides you with the **opportunity to share your perspectives on what kind of questions a holistic modelling framework, which we are developing in the SENTINEL project, should be able to answer** for the future EU energy system. Through participation in the workshop, you will (1) actively **define the research agenda for new and improved energy models**, (2) **gain first-hand insights** into major computer-based energy modelling tools, (3) **meet and network** with model developers and relevant stakeholders from policymaking, energy industry, and civil society, and (4) indirectly **impact policy advice** in the energy field for the European Commission.

AGENDA

9.30-9.50: Welcome

In the welcoming session, we put the objectives of this workshop in the context of the SENTINEL project. We will discuss the proceeding of the event and collect insights from the participants about their expectations.

9.50-10.55: Parallel thematic sessions: Defining your needs regarding the models– Round I

In virtual breakout groups, we look deeper into the essential aspects of the energy system in order to discuss their future challenges, transition needs and opportunities, which should be addressed by the energy models. Different SENTINEL modelling teams will host these parallel sessions and collect your input.

Closer to the workshop, we will send you a request to sign up for the sessions of your choice. Please note that this is an indicative distinction between the thematic sessions – it will depend on your preferences, whether all presented thematic sessions will take place.

Session 1: Transforming the power sector: increasing ambitions for GHG emissions reduction and RES targets
Carbon neutrality is linked with the decarbonisation of the power system. Although the share of renewable energy in electricity generation has increased considerably over the last decades, achieving decarbonisation will need a complete transformation of the current system and utilisation of all possible technologies.

Session 2: Sector coupling: implementing smart energy systems and accelerating the shift to sustainable mobility
Electrification of demand sectors is one of the pillars in the system transformation towards carbon neutrality. Several challenges need to be overcome and digitisation is expected to offer a helping hand in this process.

Session 3: Decarbonisation of industry and CCUS & BECCS
The decarbonisation of industry and, in particular, heavy industry could be one of the biggest challenges on the road to a climate neutral world. Technologies related to Carbon Capture Storage and Utilisation (CCUS) as well as to Bioenergy with Carbon Capture Storage (BECCS) may help to achieve this goal.

Session 4: Building and renovating in an energy and resource efficient way
The EU has a relatively high share of old and inefficient building stock. The *Renovation Wave* is targeting energy efficiency improvement, addressing in parallel the health and well-being of vulnerable citizens, while reducing their energy bills. Resource efficiency is a prerequisite in the renovation and construction process.

Session 5: Environmental aspects and implications
The application of different technologies leading to a decarbonised energy system will mean differentiated environmental impacts, related e.g., to use of recourses or space.

Session 6: Socio-economic aspects and implications, including recovery packages
The way to a decarbonised energy system should remain socially sustainable, meaning a just participation of all members of the society, as well as guaranteeing a fair distribution of costs and benefits. The recovery funds currently in the pipeline could be an ideal opportunity to ensure a fair transition towards carbon neutrality.

10.55- 11.15: Coffee break

11:15-12:20 Parallel thematic sessions: Defining your needs regarding the models– Round II

To give you the possibility to express your views on more than one aspect of the future European energy system, you will be able to join a different thematic session in the second round of virtual break-out groups, where we reshuffle the participants to provide fruitful and multifaceted discussions.

12:20-13:00 Plenary session

In the plenary, moderators of each thematic session will share insights from breakout groups with the rest of the participants. Thus, you will have the possibility to comment on the outcomes of the breakout groups, in which you did not participate. At the end of the workshop, we will present and explain how we will utilise the outcomes of the workshop as well as how you can get involved at later stages of SENTINEL.