



**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:  
 D 2.3 QTDIAN modelling toolbox**

**Version: 2**

**Due date of deliverable version 1.0: 05.2021**

**Submission date of version 1: 3.06.2021**

**Publication date of version 2: 11.11.2022**

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)	



# The QTDIAN modelling toolbox – Quantification of social drivers and constraints of the diffusion of energy technologies

November 2022  
Version 2



# SENTINEL

## Acknowledgments

The authors would like to acknowledge the support from the EC. The authors would like to thank SENTINEL colleagues for their feedback to specific sections relevant to their models and modelling themes. The authors would also like to thank the stakeholders for their relevant input on needs for QTDIAN, and participants of the ‘Energy and Society’ conference 2021 for their insights. The content of this report is the sole responsibility of its authors and does not necessary reflect the views of the EC.



## Note about contributors:

These deliverable criteria are met by the SENTINEL IASS Team.

### WP leader responsible for the deliverable:

Johan Lilliestam (IASS)

### Contributors:

Diana Süsler (IASS)

Johan Lilliestam (IASS)

Housam al Rakouki (IASS) (version 1 only)

### Contributors to Chapter 5 Model Linking:

Souran Chatterjee (CEU)

Jakob Mayer (Uni Graz)

Gabriel Oreggioni (Imperial College London)

Bryn Pickering (ETH Zürich)

Francesco Sanvito (TU Delft)

Vassilis Stavrakas (UPRC)

Please cite as:

Süsler, D., Chatterjee, S., Mayer, J., Oreggioni, G., Pickering, B., al Rakouki, H., Sanvito, F., Stavrakas, V., Lilliestam, J. (2022). The QTDIAN modelling toolbox – Quantification of social drivers and constraints of the diffusion of energy technologies. Deliverable 2.3. Version 2. Sustainable Energy Transitions Laboratory (SENTINEL) project. Potsdam: Institute for Advanced Sustainability Studies (IASS). DOI: 10.48481/iass.2022.042.

Related data set:

Süsler, D., al Rakouki, H., & Lilliestam, J. (2022). Data related to Süsler et al. (2021) QTDIAN modelling toolbox (Version 2). Zenodo.

This report is licensed under a Creative Commons License Attribution 4.0 International License



For more information about the Creative Commons License, including the full legal text, please visit: <https://creativecommons.org/licenses/by/4.0/>

# Content

List of Figures.....	6
List of Tables.....	8
Abbreviations, acronyms, and units.....	10
Glossary .....	11
Executive summary .....	12
1 Introduction.....	13
2 Modelling social aspects of the energy transition .....	15
2.1 Linking social science and energy models.....	15
2.2 Storylines and pathways: an overview .....	16
2.2.1 Defining storylines .....	16
2.2.2 Current storyline approaches .....	17
2.3 Translating storylines into modelling assumptions.....	22
3 User needs for the development of QTDIAN .....	24
3.1 Approach for the identification of user needs.....	24
3.2 User needs for modelling social aspects of the energy transition.....	25
4 The QTDIAN modelling toolbox.....	26
4.1 QTDIAN social storylines of the European energy transition .....	27
4.1.1 Objective of the QTDIAN storylines.....	27
4.1.2 Method for the storyline development.....	27
4.1.3 Social storyline descriptions .....	29
4.2 QTDIAN quantitative parameters .....	36
4.2.1 Socially feasible scaling of energy technologies.....	36
4.2.2 Policy preferences & dynamics.....	45
4.2.3 Citizens' attitudes towards renewable energy .....	56
4.2.4 Barriers to infrastructure developments.....	58
4.2.5 Citizen energy .....	62
4.2.6 Private energy demand & service.....	64
4.3 Linking storylines and quantifications.....	71
4.3.1 Socially feasible scaling and decline of energy technologies .....	71
4.3.2 Policy preferences & dynamics.....	71
4.3.3 Citizens' attitudes towards renewable energy .....	75
4.3.4 Barriers to infrastructure developments.....	76
4.3.5 Citizen energy .....	77
4.3.6 Private energy demand & service.....	78
5 Model linking.....	81

5.1 Linking QTDIAN, Euro-Calliope and WEGDYN.....	81
5.1.1 Linking QTDIAN and Euro-Calliope .....	81
5.1.2 Linking QTDIAN, Euro-Calliope and WEGDYN .....	87
5.1.2.1 Description of WEGDYN.....	87
5.1.2.2 Methods to implement the QTDIAN-Calliope-WEGDYN linkage .....	87
5.1.2.3 Linking challenges .....	88
5.2 Linking QTDIAN and demand models .....	89
5.2.1 Linking QTDIAN and DESSTINEE.....	90
5.2.2 Linking QTDIAN and HEB .....	92
5.2.3 Linking QTDIAN and DREEM .....	95
6 Discussion and conclusion.....	98
References.....	101
Appendix 1 Socially feasible scaling and decline of energy technologies.....	109
Appendix 2 Policy preferences & dynamics .....	113
Appendix 3 People’s attitudes towards renewable energy .....	114
Appendix 4 Barriers to infrastructure developments .....	116
Appendix 5 Citizen energy.....	119
Appendix 6 Energy demand .....	120

## List of Figures

Figure 1: Potentials of integrating social aspects into models, own figure based on insights from Hirt et al., 2020; Trutnevyte et al., 2019; Turnheim et al., 2015.....	16
Figure 2: Five shared socioeconomic pathways (SSPs) representing different combinations of challenges to mitigation and to adaptation, own figure based on (O'Neill et al., 2017).....	18
Figure 3: openENTRANCE storylines typology. Source: Auer et al. (2019), CC-BY-4.0.....	19
Figure 4: SET-Nav pathways. Source: del Granado et al. (2019).....	20
Figure 5: Core transition pathways to a UK low carbon electricity system, own figure after Foxon (2013). .....	21
Figure 6: The iterative process of linking storylines with multiple cross-scale quantitative models, own figure after Trutnevyte et al. (2014).....	23
Figure 7: Consideration of user needs for the development of QTDIAN. This Deliverable reports on the implementation stage. ....	25
Figure 8: Overview of the QTDIAN modelling toolbox.....	26
Figure 9: Three types of knowledge structure the storylines; based on Stavrakas et al. (2021) and Network for Transdisciplinarity Research (2021).....	28
Figure 10: The energy transition logics and their use for the QTDIAN social storylines; adapted from Foxon (2013).....	29
Figure 11: China, India, the US capacity growth. Data source: UN, 2021. ....	39
Figure 12: Capacity growth for wind and solar PV, fastest countries. Data source: IRENA, 2021. ....	40
Figure 13: Capacity growth/decline EU 28. Data source: IRENA, 2021.....	41
Figure 14: Capacity growth as percent, Wind and PV, fastest countries. Data sources: UN and IRENA data.....	43
Figure 15: Montenegro, Denmark, and Germany system change. Data sources: UN and IRENA data. ..	44
Figure 16: Bulgaria, Czechia, and Italy system change. Data sources: UN and IRENA data.....	44
Figure 17: Personal agreement for the expansion/ use of certain technologies, respondents who answered 4 or 5 (strong agreement), surveys 2017-2019, Germany. Data source: Wolf (2020).....	57
Figure 18: Progress of transmission investments since TYNDP 2018, n = 321 projects. Data source: ENTSO-E, 2020.....	60
Figure 19: Delays of transmission projects per project phase. n = 56 projects. Data source: ENTSO-E, 2020.....	61
Figure 20: Progress of storage investments since TYNDP 2018, n = 21 projects. Data source: ENTSO-E, 2020.....	61
Figure 21: Development of autoproducers in the EU 28. Data source: Eurostat, 2021.....	63
Figure 22: Energy renovation in residential buildings, sorted by overall renovation rate. Data source: Directorate-General for Energy (European Commission) et al., 2019. ....	66
Figure 23: Total number of rooms per person EU 28. Data sources: Eurostat, 2019, 2020. ....	67
Figure 24: Electricity consumption in the European Union. Data source: JRC-IDEES - Integrated Database of the European Energy System (2000-2015), 2015. ....	68
Figure 25: Electricity consumption by end uses. Data source: JRC-IDEES - Integrated Database of the European Energy System (2000-2015), 2015. ....	68
Figure 26: Total number of appliances in the EU. Data source: JRC-IDEES - Integrated Database of the European Energy System (2000-2015), 2015. ....	69
Figure 27: Final electricity consumption of lighting and appliances. Data source: JRC-IDEES - Integrated Database of the European Energy System (2000-2015), 2015. ....	70
Figure 28: Potential future development of PV autoproducers.....	78
Figure 29: Model linkages between QTDIAN and Euro-Calliope, DESSTINEE, HEB and DREEM. Adapted from (Süsser et al., 2021c).....	81

Figure 30: QTDIAN-Calliope-WEGDYN model ensemble flow chart. Adapted from Michas et al. (2022).  
 ..... 88

Figure 31: Linking QTDIAN as input for the three energy demand models; MS = Member States of the European Union. Adapted from (Süsser et al., 2021c)..... 90

Figure 32: The DREEM model's architecture as it currently stands. Source: Stavrakas and Flamos, 2020.  
 ..... 96

*Appendix*

Figure A 1: Solar PV capacity growth. .... 110

Figure A 2: Wind capacity growth. .... 110

Figure A 3: Combustible capacity growth/decline. .... 111

Figure A 4: China, India, the US capacity growth as Percent/ system change ..... 111

Figure A 5: System change EU 28. .... 112

Figure A 6: Luxembourg, Lithuania and Slovakia system change: combustible fuel decline. .... 112

Figure A 7: Share of installed electricity capacity in Greece, assumed based on NECP and Long-term strategy 2050 targets in GW ..... 113

Figure A 8: Personal stance for the expansion/ use of certain technologies, survey from 2019, n = 6,117 households, Germany. .... 114

Figure A 9: People's opinions about renewable energy in their backyard, survey 2020, n = 1051, Germany. Data source: YouGov conducted for Agentur für Erneuerbare Energien..... 115

Figure A 10: Average realisation time for wind energy projects in Germany. .... 116

Figure A 11: Expected grid developments in numbers and lengths, according to TYNDP (ENTSO-E, 2021a)..... 117

Figure A 12: Expected grid developments for storage in numbers and capacity, according to TYNDP (ENTSO-E, 2021a). .... 118

Figure A 13: Electricity production capacity by autoproducers in the EU 28. Note: the graph for solar thermal lies behind the graph for tidal, wave and ocean energy. .... 119

Figure A 14: Energy renovation in non-residential buildings, sorted by overall renovation rate..... 120

Figure A 15: Lithuania, Hungary, Sweden total number of rooms per person. .... 121

Figure A 16: Belgium, Denmark, Montenegro total number of rooms per person. .... 121

## List of Tables

Table 1: User-needs regarding social aspects and their consideration in QTDIAN.....	25
Table 2: Three social storylines of the energy transition (RE = renewable energy; EE = energy efficiency).....	34
Table 3: Model input parameters on scaling and decline of energy technologies .....	37
Table 4: Model input parameters for different policy strategies.....	46
Table 5: Model input parameters for country specific setback distances .....	46
Table 6: Dominant pathway for the EU (European Commission), based on (Lilliestam et al., 2019; V. Stavrakas et al., 2021).....	47
Table 7: Minority pathway (PAC scenario) for the EU, own analysis of Climate Action Network Europe and European Environmental Bureau (2020) and IEA Sustainable Development Scenario (IEA, 2021)..	48
Table 8: Dominant pathway for Denmark, based on the Danish NECP (Danish Ministry of Climate, Energy and Utilities, 2019) .....	49
Table 9: Dominant pathway for Finland, based on the Finnish NECP (Ministry of Economic Affairs and Employment, 2019).....	50
Table 10: Dominant pathway for Sweden, based on the Swedish NECP (The Ministry of Infrastructure, 2020).....	50
Table 11: Dominant pathways for Norway and Iceland, based on national climate plans (Ministry for the Environment and Natural Resources, 2018; Norwegian Ministry of Climate and Environment, 2019) .....	51
Table 12: Dominant pathway for Greece based on Stavrakas et al. (2021), according to NECP (HELLENIC REPUBLIC Ministry of the Environment and Energy, 2019) and Long-term strategy 2050 .....	51
Table 13: Country setback distances and density restrictions, and JRC model recommendations.....	53
Table 14: Model input parameters for people's attitudes for renewable energy .....	57
Table 15: Model input parameters for the development of onshore wind and grid development projects.....	59
Table 16: Model input parameters for the development of onshore wind and grid development projects.....	62
Table 17: Model input parameters on energy demand & services.....	65
Table 18: Projections for the development of e-mobility in the EU by 2030. Data source: (IEA, 2021a)	70
Table 19: Storyline variables and suggested quantifications for two policy pathways for the EU .....	71
Table 20: Storyline variables and suggested quantifications for two policy pathways for the Nordic countries.....	72
Table 21: Storyline variables and suggested quantifications for two policy pathways for Greece .....	73
Table 22: Share of installed electricity capacity in Greece, assumed based on NECP and Long-term strategy 2050 targets in GW .....	74
Table 23: Storyline variables and suggested quantifications for onshore wind distances and densities	75
Table 24: Storyline variables and suggested quantifications for citizens' attitudes towards renewables .....	75
Table 25: Agreement with the expansion of renewable technologies, 2017-2019, Germany, and calculation of trend and electricity mix based on Wolf (2020).....	76
Table 26: Storyline variables and quantifications for barriers to infrastructure developments .....	76
Table 27: Storyline variables and quantifications for citizen energy .....	77
Table 28: Storyline variables and quantifications for private energy demand & services.....	79
Table 29: Input parameters included from QTDIAN in Euro-Calliope (for 2030 and 2050). Note: This is work in progress and reflects the status November 2022. ....	82
Table 30: Potentials defined in Euro-Calliope. See Tröndle et al. (2019).....	85
Table 31: Parameters of the four HEB scenarios. Source: Süsser et al., 2021c.....	93



Table 32: Storyline variables and quantifications for energy demand modelling with DREEM in the Greek residential sector. Source: (Süsser et al., 2021c)..... 97

*Appendix*

Table A 1: Litigation of approved wind power plants on land. Source: Fachagentur Windenergie an Land, Status: May, 2019 (Quentin, 2019) ..... 117

## Abbreviations, acronyms, and units

CAN	Climate Action Network
CO <sub>2</sub>	Carbon Dioxide
DESSTINEE	Demand for Energy Services, Supply and Transmission in Europe model
Calliope	Energy systems model Euro-Calliope
COVID-19	Coronavirus Disease 2019
DREEM	Dynamic high-Resolution Demand-side Management model
EE	Energy Efficiency
EEB	European Environmental Bureau
EU	European Union
ETS	Emission Trading System
GHG	Greenhouse Gas
GW	Gigawatt
HEB	High Efficiency Buildings models
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
Mtoe	Million tonnes of oil equivalent
MW	Megawatt
NECP	National Energy and Climate Plan
NTC	Net transfer capacity
PAC	Paris Agreement Compatible
PV	Photovoltaic
QTDIAN	Quantification of Technological Diffusion and social constraints
RE	Renewable Energy
SENTINEL	Sustainable Energy Transitions Laboratory
SSPs	Shared Socioeconomic Pathways
TWh	Terawatt-hour
TYNDP	Ten-Year Network Development Plan
USA	United States of America
WEGDYN	Wegener dynamics model
WP	Work Package

## Glossary

An Autoproducer is an enterprise which produces electricity for their own use but for whom the production is not their principal activity.

A Logic is a general rule where and which renewable infrastructure should be built. It is a thought-puzzle adding to the Storylines/ Narratives.

A Narrative is a story or description of a situation or series of events. In the context of energy modelling, the term is interchangeably with Storyline.

A Pathway is a quantitative trajectory of a scenario combined with storylines that depart from 'reference futures', or 'business-as-usual'.

A Scenario is a quantitative description of a possible, alternative energy future, compared to a reference or baseline, and is typically used to provide information on how to reach a certain goal.

A Storyline is a qualitative narrative describing detailed a possible energy future.

A Social storyline is a narrative describing societal developments, and interactions and interdependencies between actors, technologies, and policy interventions in the European energy transition.

## Executive summary

The transition to a renewable energy-based energy system in Europe requires large changes in the way our energy is produced, transported and consumed. Because this possible future is uncertain, and real-world experimentation is impossible, energy models are useful tools to explore different possible energy futures. Such models are generally focused mainly or entirely on techno-economic aspects and do not adequately represent the social and political aspects of the energy transition, although there is broad consensus that these non-technical factors are important drivers and constraints of the transition. For example, citizens can play an important role in driving the transition by supporting developments and becoming owners of renewable energy, but they can also halt the transition by resisting infrastructure development. This calls for new approaches that support a better representation of the social and political aspects of transition in energy modelling. For this reason, we have developed QTDIAN: a Quantification of Technological Diffusion and sociAl constraiNts.

QTDIAN is a toolbox of qualitative and quantitative descriptions of socio-technical and political aspects of the energy transition that influence the overall potential, the rate of energy-related technology and service diffusion and the design of the future energy system. In version 1 of this report, we (i) presented the qualitative social storylines of the energy transition that specifically consider the social developments and dynamics of the energy transition; (ii) provided quantifications for six thematic elements of the social storylines, in formats allowing these data to be directly used in energy models. In this version 2 of the report, we have updated some quantifications and show how QTDIAN has been linked to SENTINEL energy models. We developed QTDIAN to respond to the needs of both modellers and users of the models, which we identified in SENTINEL WP1 and WP7. We developed the social storylines based on transition theory and on empirical observations of actual drivers and barriers. The output of QTDIAN is empirically founded datasets of social and political drivers and barriers of the transition, both in the form of raw data describing past and current developments and manipulated to constitute consistent quantifications of the storylines.

This report contributes to the modelling work in SENTINEL and beyond in three main ways. First, we provide three social storylines that are closely linked to different governance logics and build on observed social and political drivers and barriers in the European energy transition. This is different than most other storylines used for modelling, because ours are based on governance patterns and normative assumptions of a “good future”, and not on the more commonly used geopolitical or techno-economic storyline assumptions. Second, we provide quantitative, empirical data for several important social/political parameters that can be used together with the storylines or as separate building blocks to answer specific research questions with energy models. Third, to test the usefulness of QTDIAN, we have soft-linked QTDIAN with the energy demand models DESSTINEE, HEB and DREEM, the energy system design model Euro-Calliope, and indirectly with the economic model WEGDYN. Based on feedback from the modelling exercises, we have revised QTDIAN and publish now this updated report 2.0 to improve its usefulness for a more realistic analysis of potential future energy systems.

# 1 Introduction

Achieving the European Union's (EU) commitments under the European Green Deal, the Energy Union Strategy, and the Paris Agreement requires a significant transformation of current energy systems. The target is clear: Europe seeks to be climate-neutral by mid of the century, which requires a renewable energy-dominated energy system. The requirement for a rapid and deep decarbonisation raises the question: Who is in the driving seat to achieve a climate-neutral energy system? And how can we enable socially, economically and politically accepted and 'just transition', leaving no one behind? (European Commission, 2020a)

Models assist policy- and decision-makers in exploring possible energy futures and pathways to climate neutrality. Although computer-based energy modelling tools become increasingly good at describing technological and techno-economic developments (e.g., Koppelaar et al., 2016; Lopion et al., 2018), they are still not able to fully depict the social and political developments and dynamics of the energy transition. For example, in electricity system models, socio-political-technical features, such as the effects of renewable community ownership and the impacts of different policy instrument choices on energy system outcomes, are currently excluded (Koppelaar et al., 2016). Critical voices emerge that cost optimisation alone cannot approximate the real-world transition (Trutnevyte, 2016) and that their limited representation of societal actors, socio-political dynamics and the "co-evolving nature of society and technology" make existing energy models unable to analyse socio-technical change (Li et al., 2015).

Despite the lack of energy models in representing social impacts of the energy transition, there is an increasing awareness that "soft" factors are critical for the energy transition (Bridge and Gailing, 2020; Fast, 2013; Miller et al., 2013): societies make consumption choices and investment decisions, provide or oppose space for energy infrastructure, support or oppose policy decisions, (co-)lead transition processes and so forth. On the one hand, citizens play a facilitating role as prosumers and co-owners of community energy projects, by benefitting from on-site energy projects (Bauwens and Devine-Wright, 2018; Brown et al., 2020; Süsser and Kannen, 2017). On the other hand, public opposition towards renewable energy projects, such as onshore wind farms, as well as accompanying infrastructure, like transmission grids, slows down the energy transition (Cashmore et al., 2019; Kaldellis et al., 2013; Reuswig et al., 2016). Thus, the various social factors affecting the energy transition can accelerate or delay transition processes. Neglecting these social and socio-economic aspects in modelling could result in erroneous policy decisions. Therefore, techno-economic modelling needs to be re-examined to better reflect the social realities of the energy transition (Turnheim et al., 2015), and to allow for a better and more realistic analysis of energy system trajectories.

Linking social science and computer-based modelling is a topic currently high on the research agenda, and researchers discussed different strategies for their integration (Hirt et al., 2020; Trutnevyte et al., 2014). Various approaches for a better integration exist, but generally go no further than considering social factors as qualitative exogenous assumptions (Hirt et al., 2020; Krumm et al., 2022). Quantifying and integrating social aspects into energy models remains one of the key modelling challenges (Pfenninger et al., 2014). To allow a better depiction of real-world developments, a better representation of social aspects in energy models is essential to understand the effects of drivers and

constraints of renewable energy technologies, including the effects of political or societal paradigm changes on the speed of the transition and redesign of the energy system. With this deliverable, we advance the level of understanding for societal narratives of the European energy transition, quantify social, technical, and political aspects of the energy transition and show how these aspects have been integrated in energy models of the SENTINEL project.

We present **QTDIAN – Quantification of socio-Technological Diffusion and sociAl constraiNts**: a toolbox of qualitative and quantitative descriptions of socio-technical and political aspects of the energy transition that influence the overall potential, the rate of energy-related technology and service diffusion and the design of the future energy system. QTDIAN is not a stand-alone model but it contains socio-political-technical modelling tools ready to be integrated in other SENTINEL models and beyond, to advance the understanding of their importance in the transition. The aim of version 1.0 of this report was to (i) develop qualitative social storylines of the energy transition that take particular account of the social developments and dynamics of the energy transition; and (ii) provide quantifications for six thematic elements of the social storylines. **This is an updated version 2.0 of the report** in which we update some quantifications and show exemplarily how QTDIAN has been soft-linked with the energy demand models DESSTINEE, HEB and DREEM, the energy system design model Euro-Calliope, and indirectly, with the economic model WEGDYN. Key research questions we address are:

- What are the main social storylines describing fundamentally different ways in which the transition could take place? What are possible narratives for how it is governed?
- What are key social features/ variables that are driving or hindering the energy transition?
- How can social and socio-technical drivers and constraints be quantified so as to enable their inclusion in energy models?

The deliverable is structured as follows: In **section 2**, we introduce current approaches and research linking social science and energy modelling, to provide an overview of the status quo and research gap. Various projects have developed storylines, but the quantification of such qualitative narratives remains a challenge. The QTDIAN toolbox is based on user needs for energy modelling, identified within the WP1 and WP7 of the SENTINEL project. **Section 3** presents our approach for the identification of user needs and summarises the findings of user needs. Key user needs include the representation of social preferences and opposition, ownership, and policy preferences. **Section 4** describes the QTDIAN toolbox. QTDIAN consists of qualitative social storylines and quantitative elements, which we also link with each other. In the new **section 5**, we present the soft-linking between QTDIAN and the SENTINEL models. Finally, in **section 6**, we discuss the modelling implications of QTDIAN and outline next steps. QTDIAN is a social toolbox that can be tested by different models, such as energy demand and system design models, and will be revised according to modelling exercises.

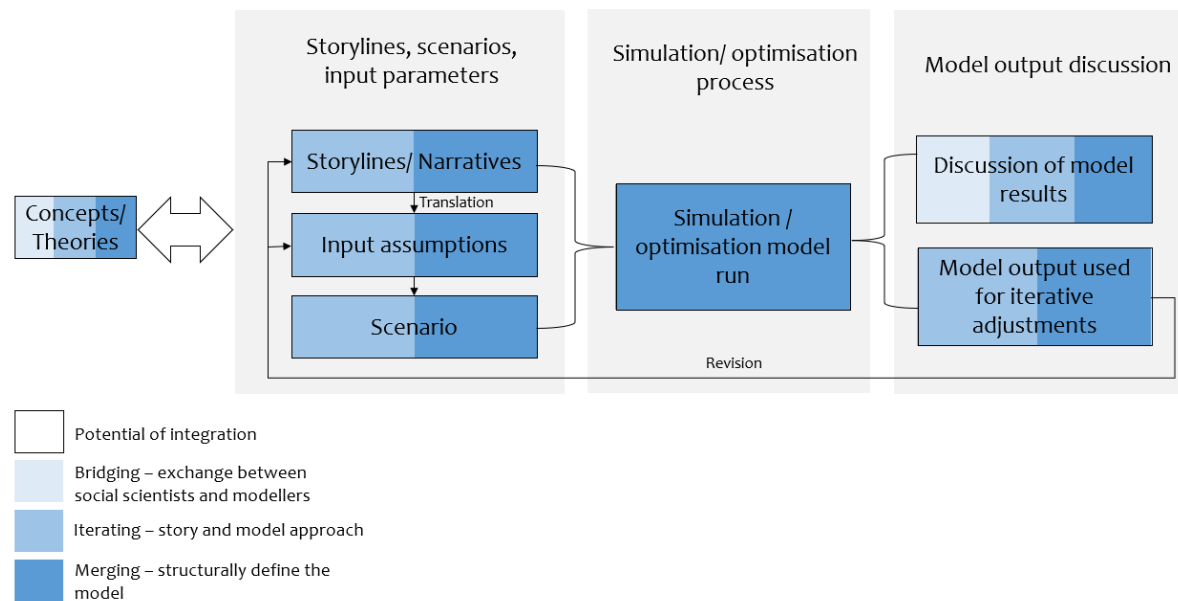
## 2 Modelling social aspects of the energy transition

### 2.1 Linking social science and energy models

Linking social science and computer-based modelling has gained increasing interest, not least because combining socio-technical research and modelling approaches can broaden the perspective on and understanding of energy transitions (Geels et al., 2016; Halbe et al., 2015; Hirt et al., 2020; Trutnevyte et al., 2019; Turnheim et al., 2015). More specifically, first, modelling can provide explicit, clear and systematic system representations that induce learning and facilitate communication about the target system (Holtz et al., 2015). Second, modelling allows us to make inferences about dynamics in complex systems and generate emergent phenomena from underlying elements and processes. Third, the use of models can facilitate systematic experiments (ibid.). Hence, combining social science and modelling can enhance interdisciplinary learning, increase realism, and support finding solutions to energy and climate challenges (Trutnevyte et al., 2019).

Current models tend to treat the social dimension of the energy transition as an exogenous narrative, or “broader societal factor” (O’Neill et al., 2014). However, differences do exist between modelling approaches, and especially agent-based models are able to simulate heterogeneous agents’ behaviour and interactions, and thus advance our understanding of societal phenomena (e.g., Squazzoni, 2010). They can provide a suitable framework for analysing the adoption decision for renewable energy technologies, demand flexibility and smart grids (Ringler et al., 2016; Stavrakas et al., 2019). In contrast, energy systems optimisation models, energy systems simulation models, power systems and electricity market models as well as integrated assessment models seem to be less able to integrate behavioural and social aspects, given their techno-economic nature.

Trutnevyte et al. (2019) differentiate between three strategies for linking models and insights from social sciences, with an increasing degree of integration between social science and models: *bridging*, *iterating*, and *merging*. In *bridging*, models and social science research are carried out in parallel and sometimes build ‘bridges’ for exchange between each other. This can be for example the case when researchers talk about common concepts, or theories. The *iterating* strategy is a “story and simulation” approach, where exogenous narratives (co-)defined by social sciences are “translated into quantitative input assumptions used by the models”, and outputs may be used for revisiting the narratives. *Merging* implies an in-depth integration, assuming that “at least the key societal factors can be modelled”, and leading to a structural modification of existing models, or creation of completely new models (Trutnevyte et al., 2019). The lower degrees of integration can often be achieved with existing modelling frameworks, whereas a higher degree of integration requires further model development, e.g. introduce endogenous dynamics of institutions or model refinements to improve actor heterogeneity (De Cian et al., 2018). **Figure 1** on the next page summarises the potentials for the integration of social aspects.



**Figure 1:** Potentials of integrating social aspects into models, own figure based on insights from Hirt et al., 2020; Trutnevyte et al., 2019; Turnheim et al., 2015.

The identified strategies can provide important starting points for expanding the link between social science and transition research, respectively, and energy modelling. For this, modellers should avoid modelling only what is easily quantifiable, and instead look for new approaches to better quantify social aspects (Pfenninger et al., 2014), which can also take place through the involvement of social scientists.

## 2.2 Storylines and pathways: an overview

### 2.2.1 Defining storylines

Storylines are qualitative narratives – detailed descriptions of possible energy futures. They are often used to embed models into a bigger picture and to justify or motivate quantitative input assumptions. Scenarios are quantitative descriptions of possible, alternative energy futures, but are no predictions. Scenario exercises can be based on qualitative storylines, quantitative modelling, or a combination of both – which is the current “state-of-the-art” (Fortes et al., 2015). Quantitative scenarios are good at describing technical details, by using empirical real-world data. In contrast, scenario narratives or storylines describe different, possible energy futures in more detail, by highlighting main scenario characteristics, relationships between driving forces and dynamics. Therefore, they can provide the logic for aspects that are quantifiable, but also encapsulate several “softer” aspects that cannot be modelled with existing methods. Future transition pathways can be defined as quantitative trajectories of scenarios combined with storylines that depart from ‘reference futures’, or ‘business-as-usual’ (Auer et al., 2019).

Two dimensions can be distinguished within the storylines (Auer et al., 2019; del Granado and et al., 2019; O’Neill et al., 2017):

- the **process** dimension: *Why* are specific developments expected to happen? What are key storylines features/variables? What are drivers and barriers, or critical uncertainties?
- the **outcome** dimension: *What* are the resulting outcomes or consequences, related to key features/variables and triggered by drivers/barriers?

By addressing these dimensions and questions, qualitative storylines enable modellers to take a broader perspective of future developments and system changes – not only in terms of technological innovations and deployment pathways, but also in terms of social acceptance, political feasibility, and roles of decision-makers, among others. Furthermore, they help to harmonise assumptions and increase robustness and consistency of scenarios (Robertson et al., 2017; Trutnevyte et al., 2014).

### 2.2.2 Current storyline approaches

Scientists have developed different approaches to energy- and climate-related storylines and pathways. Here, we provide an overview of common, recent methodological approaches and frameworks used. What they all have in common is that the developed storylines tell different stories of possible developments of the energy system. Some of them focus rather on the global level, other consider changes within a national energy system. Among some storylines there are clear overlaps, as they consider different levels of climate and energy ambitions, the importance of specific actors (e.g., society, market, governments), and/or specific scales (e.g., centralised vs. decentralised), but with different underlying logics driving the transition.

#### *Narratives for shared socioeconomic pathways (SSPs)*

One of the most used sets of storylines are the narratives for shared socioeconomic pathways (SSPs), developed and used by the IPCC. These are “broad descriptions of future conditions that are relevant for both the analysis of emissions drivers and mitigation strategies, and the analysis of societal vulnerability to climate change, climate impacts and potential adaptation measures” (O’Neill et al., 2017). These narratives are one component of climate change pathways/ scenarios. The scenarios are used to derive different greenhouse gas emissions scenarios with different climate policies and are also used to produce the IPCC Sixth Assessment Report on climate change, due in 2021. The narratives are part of five SSPs that represent different socio-economic different combinations of mitigation and adaptation challenges (**Figure 2** on the next page).



**Figure 2:** Five shared socioeconomic pathways (SSPs) representing different combinations of challenges to mitigation and to adaptation, own figure based on (O'Neill et al., 2017).

The SSP narratives are a set of five qualitative descriptions of future changes in six broad categories (O'Neill et al., 2017):

- demographics: assumptions regarding population development and urbanisation;
- human development: assumptions on education, gender equality, societal participation, etc.;
- economy and lifestyle: assumptions about growth, globalisation, consumption, etc.;
- policies and institutions: assumptions concerning environmental policy, policy orientation, etc.;
- technology: assumptions regarding development, transfer and energy intensity;
- environment and natural resources: assumptions about fossil constraints, environment, etc.

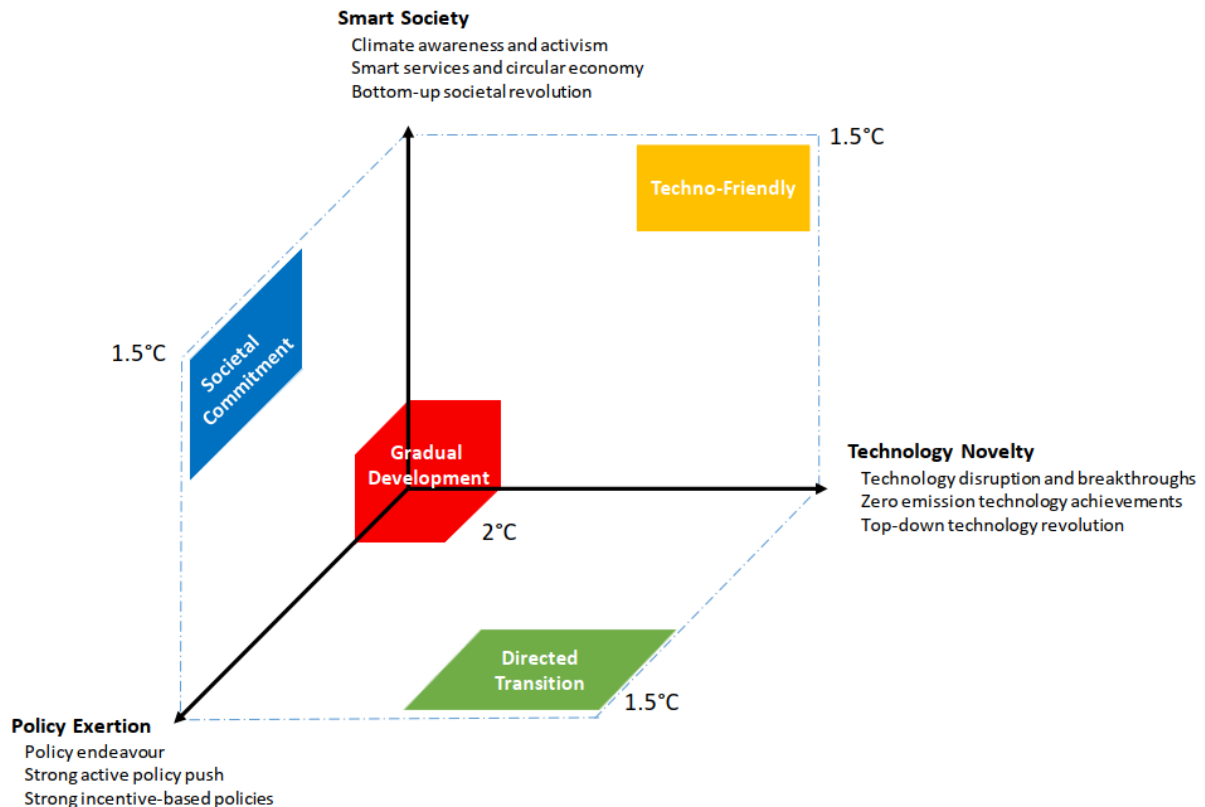
Different projections are defined, such as for population growth, GDP and urbanisation, within the different SSPs, which will then lead to different emission scenario ranges. The narratives of global societal development have been developed in expert discussions and are “designed to span a relevant range of uncertainty in societal futures” (O'Neill et al., 2017). As O'Neill et al. (2017) emphasise, the span has been defined via a backcasting approach by identifying particular outcomes, and then considering the specific features and drivers leading to each outcome. Detailed descriptions of the storylines are available in O'Neill et al. (2017). It is important to note that the SSPs narratives have a global framing. In the context of the energy transition, however, many of the challenges of receiving societal acceptance for energy infrastructure, planning and building energy projects, and defining and implementing policies, will happen on national, regional and local levels.

### *OpenENTRANCE storylines*

In the framework of the OpenENTRANCE project, Auer et al. (2019) developed four storylines describing possible future developments of a low carbon European energy system. They developed a three-dimensional storyline typology with different degrees of exposure of uncertainty/ disruption. Beginning from this starting point, the researchers themselves were the storytellers. They developed four storylines:

- Gradual development;
- Techno-friendly;
- Directed transition; and
- Societal commitment.

The authors state that they do not have any preference over the one or the other, and that they expect they all describe possible developments. Their storylines are a combination of two to three uncertainties/ disruptions to highlight the possible future developments. Auer et al. (2019) defined storyline drivers, features and uncertainties characterising the qualitative storylines/ narratives. Three dimensions – namely smart society, technology novelty and policy exertion – and the combination of those results in the storylines. **Figure 3** provides an overview of the openENTRANCE storylines typology.



**Figure 3:** openENTRANCE storylines typology. Source: Auer et al. (2019), CC-BY-4.0.

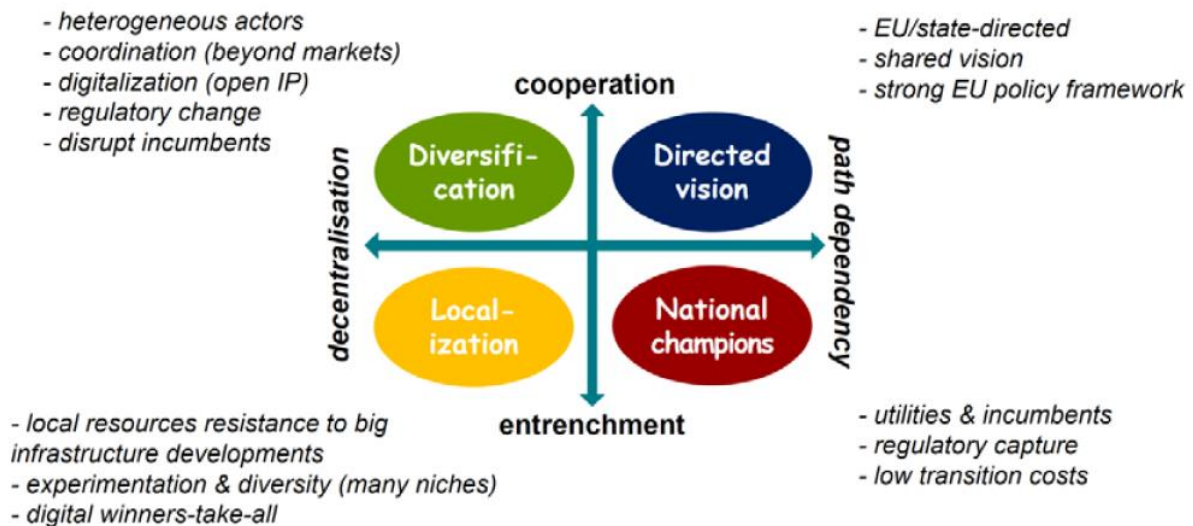
For each storyline, Auer et al. (2019), provide a general description, and descriptions of technology policy/market and society, highlighting some unique properties for each. Regarding the social aspects of the energy transition, the storylines address society's attitudes and lifestyle changes, e.g., willingness of the society to invest in renewable energies or promote them, as well as changes in demand. A detailed description for each storyline is available in Auer et al. (2019). In a second step, researchers from the openENTRANCE project have also developed quantifications for them at pan-European level. Different parameters, such as costs, prices, resource potentials, technology portfolios available, technological learning rates, and willingness to pay, have been integrated in the quantitative scenarios (Auer et al., 2020).

### *SET-Nav pathway storylines*

In the SET-Nav project, del Granado et al. (2019) developed four distinct alternative pathways of future change in the EU energy system. They proposed a 2x2 scenario typology to combine two key uncertainties – the level of cooperation and the level of decentralisation – into four storylines, spanning a wide possibility space (**Figure 4** on the next page). The distinct storylines are called:

- Diversification
- National champions
- Localisation
- Directed vision.

The researchers defined for each pathway qualitative features and positioned them under the dimension cooperation vs. entrenchment and decentralisation vs. path dependency.



**Figure 4:** SET-Nav pathways. Source: del Granado et al. (2019).

For each storyline, del Granado et al. (2019) describe key elements, the storylines for the policy framework, and the project plan emphasis on priority area and directed innovation. Regarding the social and behavioural aspects, the storylines make demand assumptions. Overall features and assumptions are described in del Granado et al. (2019). Based on a common set of pathway features and assumptions, such as regarding tech costs and learning costs, they introduced different values for each pathway and reflected them as input by the SET-Nav modelling team. For each storylines, they performed different scenario runs.

#### *Storylines informed by multi-level perspective*

Recent research drew qualitative insights from socio-technical transition studies, specifically the multi-level perspective, to develop new quantitative scenarios (Hof et al., 2020; Pregger et al., 2019; Savvidou and Nykvist, 2020; van Sluisveld et al., 2020). Van Sluisveld et al. (2020) used two different transition narratives to bridge socio-technical transition studies and integrate assessment modelling by developing qualitative socio-technical storylines and translate them into quantitative scenarios:

- Technological substitution
- Broader regime change

The first is driven by incumbent actors, “who are focussed on replacing existing socio-technical elements with versions that better fit with the new environment”. The second one is driven by new actors with a negative attitude towards large-scale technologies. Instead, it includes “a shift to a new socio-technical system, based on the breakthrough of radical niche-innovations that entail not only technical changes but also wider behavioural and cultural changes and new user practices and institutions” (ibid). Van Sluisveld et al. (2020) defined different patterns of transition for different renewable energy

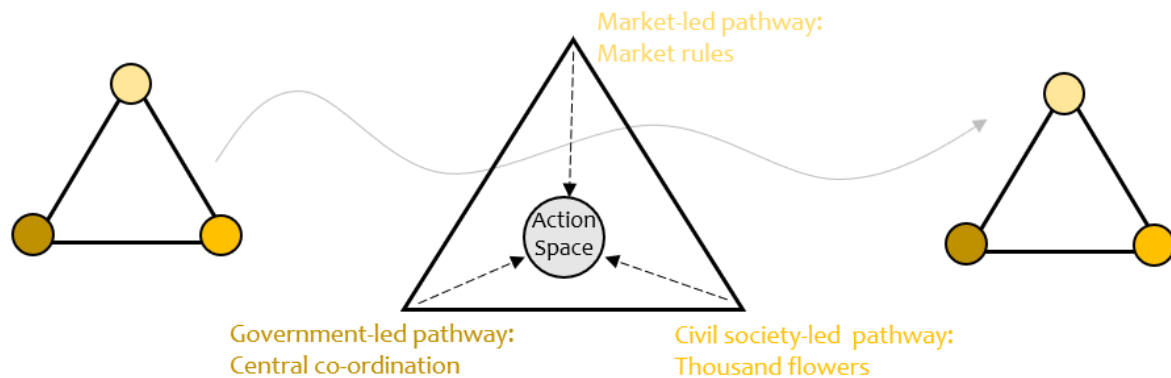
technologies in different countries to promote or weaken the re-presentation of a niche-innovation in the respective scenario.

Hof et al. (2020) used a similar approach: they linked three models to investigate two contrasting transition narratives on the role of actors in meeting greenhouse gas reduction targets. The narratives were based on an analysis of actors' preferences, behavioural and cultural changes and social networks, and technological and social niche-innovations, and they informed the narrative-driven scenario development. Hence, their scenarios are based on socio-technical transition analysis. For example they use different narratives for assumptions on the share of onshore wind energy in the electricity generation by 2050.

### *Realising Transitions Pathway storylines*

The Transition Pathway storylines for a low-carbon electricity system in the UK were also developed from the multi-level perspective of transition dynamics. Foxon (2013) and Barton et al. (2018) describe a set of three Transition Pathways to examine the influence of different governance arrangements on achieving a low-carbon future. The pathways are differentiated by their three interlinked governance logics – government-led, market-led or civil society-led – which define the action space. As illustrated in **Figure 5**, the three core transition pathways are:

- Market rules (market-led),
- Central co-ordination (government-led), and
- Thousand flowers (civil society-led).



**Figure 5:** Core transition pathways to a UK low carbon electricity system, own figure after Foxon (2013).

The development of the pathways started with the narrative storylines of plausible evolutions of the UK towards a low carbon economy to 2050. To develop the narratives, Foxon et al. (2010) made use of the multi-level perspective to characterise the existing energy regime, its internal tensions and landscape pressures on it, to identify dynamic processes at the niche level and specify interactions giving rise to, or strongly influencing, transition pathways. For each pathway, they define key characteristics, including key technologies, concepts, multi-level pattern, learning processes and infrastructure aspects etc. The role of societal and behavioural aspects is strongest in the “Thousand flowers pathway”, mentioning citizens as important actors and drivers of community-led initiatives. The outline narratives underlying each of the pathways were based on a review of UK and international energy scenarios and approaches to scenario building, as well as workshops and a set of interviews. Further stakeholder dialogues and

consultations to also place later in the context of the analysis of the pathways (Foxon, 2013). Beyond the qualitative storylines, the researchers also developed an iterative approach for the quantification of the pathways coherent and consistent with the storylines. The quantification as such was based on a spreadsheet analysis and not on a techno-economic model. More detailed information on the transition pathway storylines are provided in Foxon et al. (2010) and Foxon (2013).

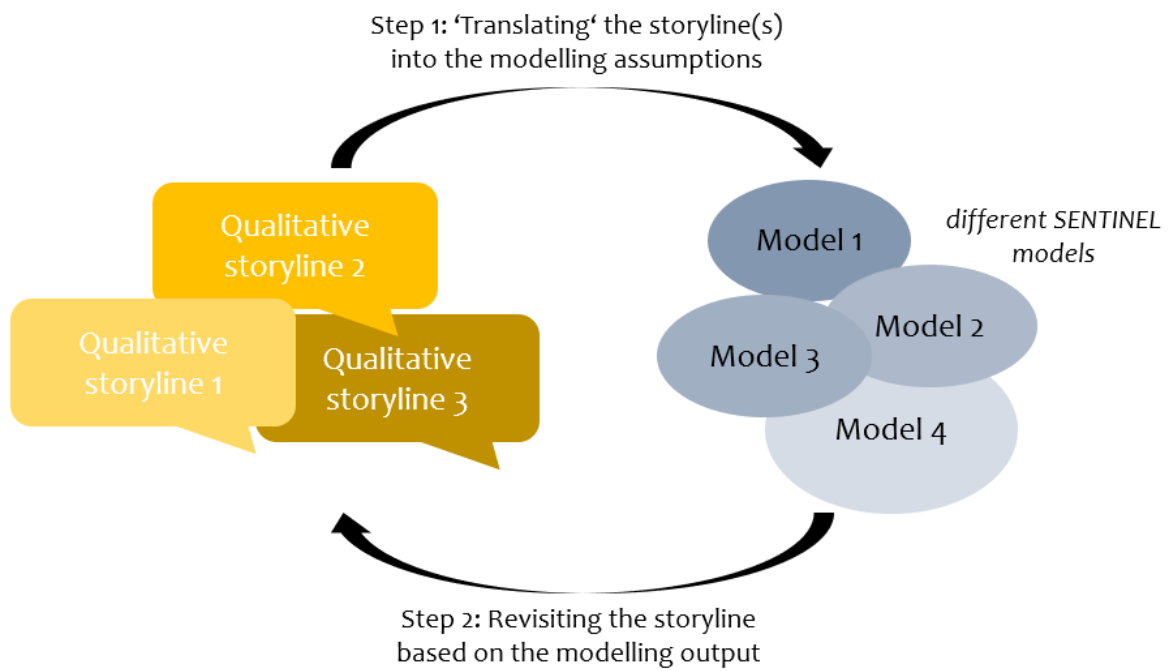
## 2.3 Translating storylines into modelling assumptions

The various storyline approaches developed in the past have contributed to widen the perspective of the energy transition towards social and political transition aspects. However, before storylines can unfold their impact in models, they must be 'translated' into quantitative assumptions that are both coherent and consistent with the storylines. Quantifying and integrating these aspects into energy models is still one of the key modelling challenges (Pfenninger et al., 2014; van Sluisveld et al., 2020). As Overland and Sovacool (2020) pointed out, social aspects are often hard to specify in numbers, and hence stay in conflict with the "clearer and more concrete" nature of natural and technical science. Thus, 'translating' the storylines will always be subjective to some degree (Trutnevyte et al., 2014).

Trutnevyte et al. (2014) discuss an iterative process of linking storylines with multiple models, as illustrated in **Figure 6** (next page). This process seems to be very promising as it allows for a closer integration of storylines and quantification than the bridging strategy but does not need a very close linking and related effort than involved in the merging strategy (compare **section 2.1**). **Step 1** is to 'translate' the qualitative storyline into a set of harmonised assumptions needed for conducting the model runs. It must be specifically tailored to the respective storyline. Van Sluisveld et al. (2020) described the translation process by saying:

*"In terms of actual implementation, translation is considered the process of locating the right context variables in the model and setting new values to the default parameterisation. These context variables are specific to the model, leaving much of the translation to the interpretation of the modeller."*

The interpretation, we believe, should be done together between the modeller and storyline developer (e.g. social scientist), because the modeller tends to ignore aspects that (s)he cannot model, and thus you might end up with insufficient results. Nevertheless, this step will already lead to a narrower representation of the qualitative storyline, because quantitative models can only capture a part of the bigger, qualitative picture of the energy system (Trutnevyte et al., 2011). However, quantitative assumptions should leave enough flexibility for the quantitative models to express their perspective and contribute with other, model-specific assumptions (Trutnevyte et al., 2014). As Trutnevyte et al. (2014) points out, "it is desirable to harmonise the list of the assumptions so that they could be implemented in all of the models", such as in different SENTINEL models. In a **second step**, after the model runs, the storyline characteristics are checked for their consistency with the modelling results. In consequence, the storyline or the multiple models can be revised – both are not fixed and can be also revised based on new real-world events, new data sources, stakeholder consultations etc. (ibid.).



**Figure 6:** The iterative process of linking storylines with multiple cross-scale quantitative models, own figure after Trutnevyte et al. (2014).

## 3 User needs for the development of QTDIAN

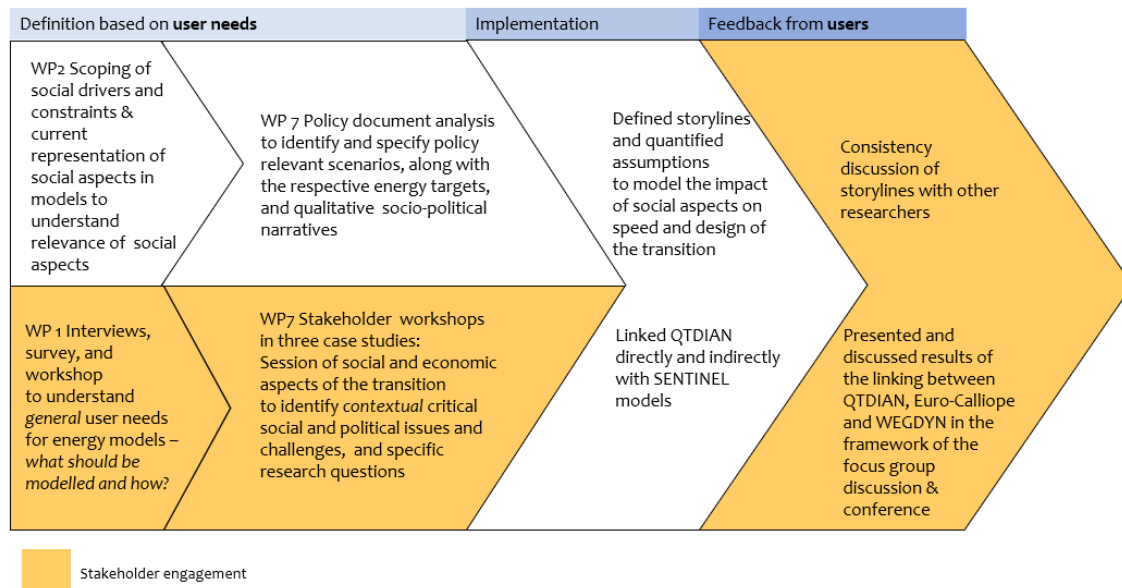
Stakeholder engagement has gained attention in energy modelling. Stakeholders are increasingly included in the narrative development process to combine qualitative storylines with quantitative modelling (e.g., McGookin et al., 2022; Rodrigues et al., 2022), though most modelling studies included stakeholders ex-post at the end of the modelling process to validate the results (McGookin et al., 2021). In SENTINEL, we see the needs of model users as the central aspect to build and improve models in a way that they are relevant from the perspective of working with them in different contexts. Therefore, we seek to integrate the specific social aspects that model users perceive as important for the energy transition (as drivers or barriers) and at the same time as underrepresented or ignored by energy models. In the following, the QTDIAN toolbox picks up the social aspects described by users in the extensive past and ongoing stakeholder work in the project as important but missing in energy models, and create social storylines, including quantifications of the key variables, for use in the updated SENTINEL models on the SENTINEL modelling platform<sup>1</sup>. Deliverable 2.4 (Madrid-López et al., 2021) provides a more comprehensive description of the user needs. Here, we provide only a brief overview of the approach and identified user needs.

### 3.1 Approach for the identification of user needs

We identified a range of different user needs for model improvements based on the stakeholder engagement processes of SENTINEL (WPs 1 and 7; cf. Gaschnig et al., 2020; Stavrakas et al., 2021), as well as in analysis of policy documents and studies. **Figure 7** on the next page provides an overview how user needs have influenced the definition and implementation of QTDIAN. We firstly discussed different social and political storyline aspects with stakeholders in the context of three stakeholder workshops to discuss and rank the importance of social and political drivers and barriers that should be captured in energy models (results are presented in (Süsser et al., 2022b)). Second, we discussed the consistency of the storylines with other researchers, both within the project and in an interactive workshop the at 5<sup>th</sup> Energy & Society conference 2021. Furthermore, we presented and discussed the storylines, the linking approach and first results at the Energy Modelling for Europe conference 2021 and in a focus group on “Socio-economic impacts of the energy transition”.

---

<sup>1</sup> <https://sentinel.energy/model-catalog/>



**Figure 7:** Consideration of user needs for the development of QTDIAN. This Deliverable reports on the implementation stage.

### 3.2 User needs for modelling social aspects of the energy transition

The stakeholder engagement process revealed several needs for QTDIAN by modellers and model result users. **Table 1** provides a summary of identified user needs, how QTDIAN has been designed to meet the user needs and what research questions are related to it.

**Table 1:** User-needs regarding social aspects and their consideration in QTDIAN

User need/Gap	How QTDIAN is designed to meet this need	Related research questions
<b>Local opposition towards energy infrastructures</b>	Social storylines include opposition against different types of assets (renewable power technologies, accompanying transmission infrastructure); quantification of amount and time of delays as input assumption	How does local opposition against renewable energy projects and energy infrastructure projects affect the speed and direction of the overall transition?
<b>Social acceptance/ preferences towards renewable energy technologies</b>	Social storylines include acceptance of different technologies, infrastructures; statistics on public opinions about technologies	How would future renewable energy landscapes look like if they are based on people's preferences? How does the deployment of (regionally, nationally) preferred renewable energy technologies affect potential, overall cost and system design?
<b>Citizen and community ownership</b>	Social storylines include ownership and (de)centralised tech system design; quantifications of autoproducers and citizen energy companies	How does ownership affect the system design?
<b>Policy preferences and dynamics</b>	Social storylines include policies and potential policy changes, as well as address the role of social movement towards policy decisions; quantification of majority and minority policy strategies as input assumption	How do policy changes affect the development of renewable energy?
<b>Social technological scaling / scaling of the economy</b>	Social storylines include energy system characteristics; quantification as input assumption	Does the speed of technology deployment affect the speed and direction of the energy transition?

There are also user needs we could not consider, but which could be taken further in future work, such as energy poverty and a just transition more broadly. **Section 4** describes the QTDIAN modelling toolbox in the more detail that touches upon the user needs.

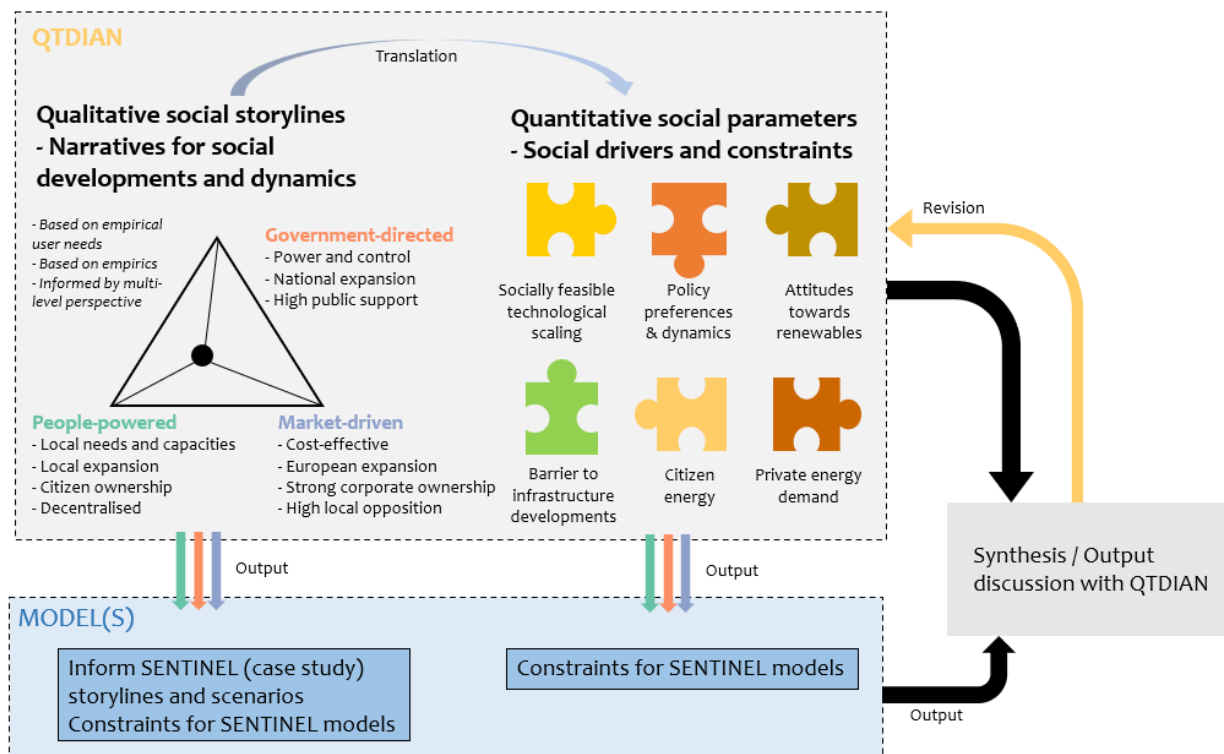
## 4 The QTDIAN modelling toolbox

QTDIAN is a social modelling toolbox that deals with social drivers and constraints of technological diffusion. It is not a stand-alone model, but rather a 'toolbox' that captures different social, political, and technological aspects to better understand their influence on the renewable energy development and to allow the explicit inclusion of such factors in the models of SENTINEL. These factors are represented qualitatively and, where possible, operationalised quantitatively.

QTDIAN consists of two main elements (see **Figure 8**):

- (i) Qualitative social storylines of social developments and dynamics that inform and expand the SENTINEL storylines and scenarios (details in section 4.1);
- (ii) Quantitative input assumptions driven by and representing the qualitative storylines; quantifications can be operationalised as social drivers and constraints, they consist of a logic and of datasets ready to be integrated/plugged into existing energy system models (details of parameters, see section 4.2; links to storylines, see section 4.3).

To improve the representation of social aspects of the energy transition in existing energy models, QTDIAN provides data and sets of assumptions that are ready to be integrated in energy models. Furthermore, QTDIAN can "receive" model output to synthesise and discuss modelling results. It is the process of interpreting model output against social realities and discusses the societal implications of different energy scenarios.



**Figure 8:** Overview of the QTDIAN modelling toolbox.

The QTDIAN data as described below is the updated Version 2 (Süsser et al., 2022a). The data set Version 1 (Süsser et al., 2021b) has been slightly updated, following the modelling linking process. In Section 5, we describe how QTDIAN data have been used in different SENTINEL suite models.

## 4.1 QTDIAN social storylines of the European energy transition

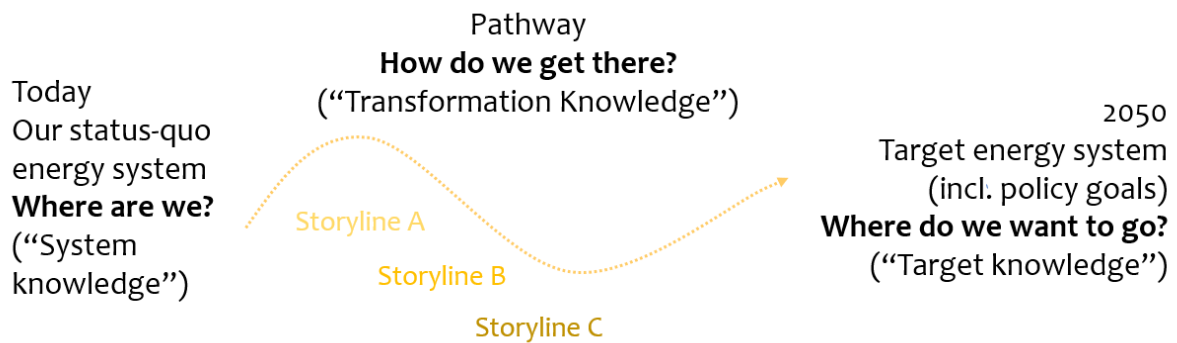
The first element of QTDIAN are *social storylines* – narratives describing not only technological innovations and deployment pathways, but also societal developments, and interactions and interdependencies between actors, and policy interventions in the European energy transition. Qualitative storylines can thus enable modellers to take a broader perspective of future developments and system changes and explore the “what-if” questions of possible future energy systems.

### 4.1.1 Objective of the QTDIAN storylines

The objective of the QTDIAN storylines is to provide a theoretically and empirically founded understanding for societal drivers and constraints of the energy transition, as the first step towards including social dynamics in energy models. So far, most scenarios focus on technical, economic, and partially political aspects underlying different energy pathways, while often neglecting the social realities. In comparison to existing storylines, which typically focus on technological and economic aspects, we build *social* storylines that have at the core the needs, preferences and capacities of citizens and their role within the energy transition. With QTDIAN, we provide three social storylines that can be applied to broaden the perspectives of transition storylines and pathways and to translate storylines features/ variables into model assumptions.

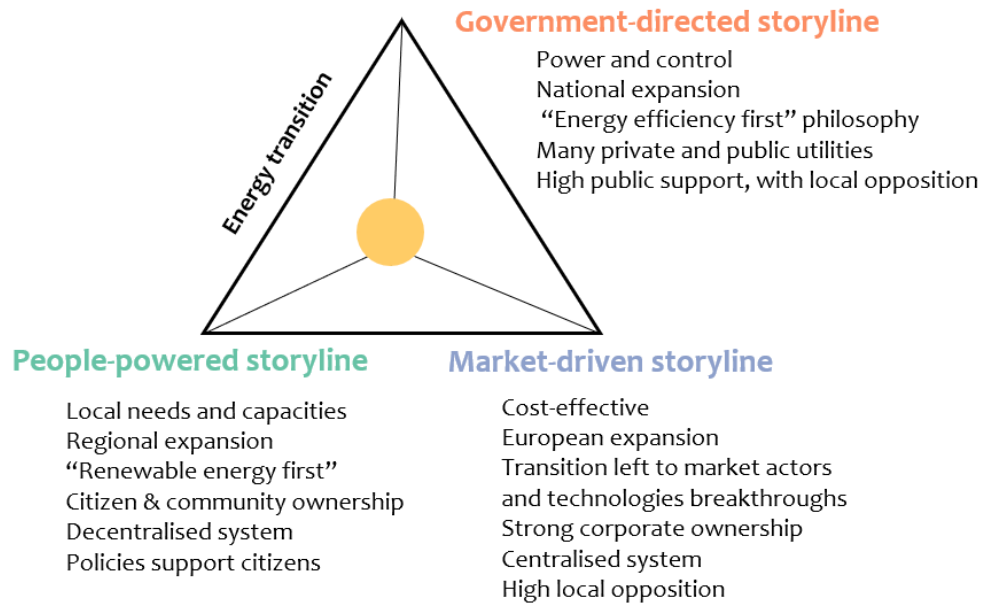
### 4.1.2 Method for the storyline development

In the context of the storyline development, we engaged with stakeholders in the framework of WP1 and WP7 of the SENTINEL project, to combine multiple perspectives and sources of expertise about possible future developments, different drivers and challenges, and the role of society in the energy transition. The interaction with stakeholders in three case studies (Greece, the Nordic, and the EU) were structured along “Three types of knowledge” (Network for Transdisciplinarity Research, 2021) (**Figure 9** on the next page). In this, the stakeholders were our *storytellers*, who provided general and contextual specific social, economic, and political insights for the SENTINEL case studies, telling their stories of how the transition will or should happen and how the European energy future will look. This approach helped us to identify key societal drivers and barriers and derive at a potential “development corridor”. For the development of our different QTDIAN storylines, we also applied the three types of knowledge to describe and address different variables and features of *Where we are?* (“System knowledge”), *Where do we want to get to?* (“Target knowledge”) and *How do we get there?* (“Transformation knowledge”) for each storyline.



**Figure 9:** Three types of knowledge structure the storylines; based on Stavrakas et al. (2021) and Network for Transdisciplinary Research (2021).

To systematise the narratives and describe types of narratives, rather than each stakeholder’s individual story, we draw on the framework of governance logics defined by Foxon (2013), Foxon et al. (2010) and further developed in Lilliestam et al. (2019). We observe that many of the factors that drive and constrain the energy transition are not technical or economic (Bridge and Gailing, 2020; Sovacool et al., 2022), but rather concern how the transition should take place and with what final outcomes for whom. That is why the discussions about the transition are often centred on questions about governance. The governance-centred Logics framework is based on precisely these factors while also being rooted in socio-technical transitions research (Geels, 2002; Geels et al., 2017), which accounts for social and political developments and transition dynamics. The Logics framework poses that the development space of possible energy transition pathways is a triangle with three distinct, competing logics in its corners (see section 4.1.3, Fehler! Verweisquelle konnte nicht gefunden werden. on the next page): a state-centred logic, in which the central government leads or carries out the transition; a market-centred logic, in which the government sets the framework but leaves all other decisions to market actors; and a grassroots-centred logic, in which the transition is carried out locally based on local needs and with the capacities available to each community. These logics have been also observed in European politics, as positions of different political parties/ideological positions (Lilliestam et al., 2019; Thonig et al., 2021).



**Figure 10:** The energy transition logics and their use for the QTIDIAN social storylines; adapted from Foxon (2013).

Based on the governance Logics framework, we developed three socio-political storylines of possible future energy systems in Europe: a *people-powered*, a *government-directed*, and a *market-driven* transition storyline. The three QTIDIAN storylines present ideal-typical developments, each driven by different sets technological and institutional changes, and each triggering different engineering and social challenges. In reality, a mix of the storylines may occur, they could exist in parallel depending on the contexts, or we could even experience switches from one storyline to another (Lilliestam et al., 2019; Thonig et al., 2021). Such “logic-mixing” can be done in the scenario-building exercise based on the QTIDIAN data. For each of the storylines, we identified key variables or features driving or hindering possible future developments. In section 4.3, we then quantify specific variables, for each storyline, in a way that is supported by empirical observations. We are the storyteller, but the stories are based on needs, research questions, and narratives identified in the SENTINEL stakeholder engagement process. The storylines have been discussed with researchers and other stakeholder to develop storylines that are consistent and differentiated.

#### 4.1.3 Social storyline descriptions

As shown in Fehler! Verweisquelle konnte nicht gefunden werden., QTIDIAN consists of three storylines of the energy transition. The storylines focus on development in the electricity sector, and address only some transition aspects in the heating/cooling and transport sector. We decided for this focus to ensure that the storylines do not lose consistency over the complexity of aspects to be included, and because electrification will also play a key role in the heating and the mobility sector.

Each storyline is characterised by features with different characteristics. Two key developments/assumptions regarding energy policy and citizen awareness that underly all three storylines:

- *EU climate neutrality by mid-century or earlier:* the EU has decided to become the first climate-neutral continent and the European Green Deal is a central strategy for the EU to navigate the transformation to a sustainable and climate-neutral economy and society by 2050 (COM(2019)

640)<sup>2</sup>. The Green Deal includes the updated 2030 Climate Target Plan, which aims at reducing net GHG emissions by at least 55% by 2030 (compared to 1990). This is a significant increase relative to the previous target of 40% emissions reduction, set in the 2030 climate and energy framework of the EU. The Deal's action plan also includes the aim to provide “clean, affordable, and secure energy” (COM(2019) 64)<sup>3</sup>. The EU's energy transition framework for the post-2020 period is defined in the policy package *Clean energy for all Europeans*<sup>4</sup> – and that name also sets the European long-term energy political ambition, and marks a significant step towards the implementation of the Energy Union Strategy. We assume that the EU pursues these targets.

- *Citizen awareness for climate change:* European citizens have a high awareness for climate change, and the majority supports actions to reduce greenhouse gas emissions (European Commission, 2019a). This fact is also reflected in growing climate change movements, like, for example, Fridays for Future or Extinction Rebellion. Moreover, citizens also support the EU's energy policy objectives: they acknowledge its role in shifting from fossil fuels to renewable energy sources to combat climate change, decreasing energy consumption across the EU and facilitating more competitive prices for consumers (European Commission, 2019b). For example, 72% of the consumers state that their decisions have been influenced by the EU Energy Label when buying appliances (ibid.). We assume increasing citizen awareness of climate action and mitigation measures, and thus a generally positive and supportive environment for different types of climate policy and governance expressed in each storyline.

### People-powered storyline

*Where are we?* The *people-powered* transition storyline emerges from protest against fossil and nuclear energy-based and centralised power structures (Dietz and Garrelts, 2014). In this, large corporations hold the market power and act in collusion with policymakers to maintain control over the energy system. The current *energy order* has led to an undemocratic energy system, and therefore decarbonisation requires more than replacing technologies – it requires societal change and moving away the centralised energy system model (**problem**).

*Where do we want to go?* Hence, the **solution** is to reduce the role of corporations and develop citizen and cooperative energy, as well as small- and medium-scale companies close to the people: Energy for the people by the people. These democratic forms of energy cooperation play a key role in achieving energy and climate targets. Consequentially, the subnational regions are the central geographical and political units and the main scope of system planning.

**Citizens and municipalities play an active role in the energy system of 2050.** Half of EU households produce renewable energy by 2050 (Kampman et al., 2016) – either as individuals or as partners in community-owned energy projects. Municipalities and regional utilities support the local, decentralised energy transition. The early success of community-owned energy projects has spread across Europe and

<sup>2</sup> <https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640>

<sup>3</sup> <https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1596443911913&uri=CELEX%3A52019DC0640#document2>

<sup>4</sup> [https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans\\_en](https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en)

became a common practice (Hewitt et al., 2019). Many citizens are prosumers (producers and consumers of their self-produced energy) and benefit financially from local energy generation. The diversity of actors in the energy sector is high, with many small and medium size enterprises involved, such as planning offices and installation and maintenance services, which are close to the people.

**Engaging citizens through collective energy actions** reinforced positive social norms and promoted social awareness for the importance of individual actions to combat climate change. This also led to a lower household energy consumption and high acceptance for behavioural changes that support demand-side flexibility. Similarly, people are adopting collective solutions such as public transport and car-sharing, so that not only are individual cars decarbonised (electric cars powered by renewable electricity), but there are also fewer cars on the streets and people fly less than today. However, they do not make large investments in energy efficiency measures, including building retrofits, beyond baseline improvements after regular investment cycles.

The resulting technological energy system is largely characterised by a **decentralised energy production** with smaller units and local small and medium size storage systems. In contrast, grid infrastructure is minimised, as generation is located near (or at) the places of consumption. Furthermore, it focuses on regional transmission, with no new transmission lines and no grid-level storage. Cross-bord fuels exchange of hydrogen and synthetic fuels is also limited to a mainly national autarky.

*How do we get there?* **People are the “engine” of the energy transition:** Local needs, preferences and capacities determine the energy transition. People want to participate in the energy transition – they want energy democracy and energy citizenship.

The **participation of citizens and communities in energy projects defines the transformation** of the energy system. The population embraces a **“Renewable Energy First”** mentality. People participate individually and collectively in renewable energy projects, invest in them, and are (co-)own energy technologies.

Diverse stakeholder groups are actively participating in the energy transition. **Acceptance for renewable energies is high among the public and in the local communities**, and there are hardly any local counter-movements. The strong climate movement supports a positive framing of the energy transition, which offers new opportunities and creates local benefits for the population: it helps to generate local returns for other (infrastructure) projects, create jobs, and improve air quality (cf. Süsser and Kannen, 2017; Walker et al., 2014). People actively support the development of local energy infrastructure projects from which they can benefit. This further contributes to prevent energy poverty (Inês et al., 2020). In contrast, the population opposes large-scale renewables projects and transmission grid extensions, leading to delays and cancellations.

**The EU is striving towards its ambitious climate and energy policy targets.** The COVID-19 crisis marked the starting point for “building back better”, and a just, inclusive energy transition that leaves no one behind. This includes not only making clean energy available to all Europeans, but also implementing policies that give more responsibility and opportunities to the population, so that it becomes a just

transition *by and for* citizens. In line with the Energy Union Strategy, “citizens take ownership of the energy transition, benefit from new technologies to reduce their bills, participate actively in the market, and [...] vulnerable consumers are protected” (COM/2015/080)<sup>5</sup>. Energy policy frameworks support citizens: renewable energy support schemes provide incentives for small and medium enterprises to invest and raise awareness for collective actions.

### *Government-directed storyline*

*Where are we?* The starting point for the *government-directed* storyline is that the EU as a whole and its Member States emit too many greenhouse gases (**problem**). Europe has decided to become the first climate-neutral continent by 2050, and Member States are stepping up the actions to replace carbon-intensive technologies and practices with zero-carbon ones, but to do so in a controlled, secure way.

*Where do we want to go?* Consequently, the **solution** is for the EU and its Member States to drive and guide the energy transition by replacing existing production assets with climate-neutral ones. Security plays a major role in the public and political debate. Maintaining control over both the **stability of energy supply and over the pace and direction of the transition** are central features of energy and climate governance. Therefore, governments respect security concerns by carefully implementing changes, with policies closely following their detailed and elaborated master plans. As national governments are the main drivers of transition, countries are the key geographical and political entities and the main area of system planning.

**Fewer citizens are (co-)owner of renewable energy.** As control is central, governments carefully steer the transitions, for example through tenders and quotas, to keep the transition on course, not too fast and not too slow. This governance style leads to a medium diversity of actors with public and private utilities as central actors in the transition, while bottom-up initiatives and citizen energy are not strongly represented.

The governments embrace the “**Energy Efficiency First**” philosophy. This leads to high deep renovation rates and a reduction in private energy consumption, especially with regard to heating and cooling demand in buildings. In line with the view that climate change is caused by the use of the wrong technologies, transport systems are changing only moderately, with the growth of public transport in cities keeping pace with the growth of transport demand and a shift from internal combustion to electric mobility; the number of cars on the road remains largely constant, so do flights.

The resulting technological energy system is **dominated by centralised energy generation**, with national boundaries clearly visible in the system architecture. Grid infrastructures are built as far as necessary, with a national focus and grid-scale storage. Transmission is mainly on a national level, but also between neighbouring countries to support the European common energy market. Same holds for cross-border fuels exchange: hydrogen and synthetic fuels is also limited.

---

<sup>5</sup> [https://ec.europa.eu/energy/topics/energy-strategy/energy-union\\_en](https://ec.europa.eu/energy/topics/energy-strategy/energy-union_en)

*How do we get there?* **The EU and Members are implementing policies to meet ambitious climate and energy targets by replacing current technologies with zero-carbon technologies.** The *Just Transition Mechanism* has been used to drive investments in clean energy infrastructures, retrain workers in the fossil fuel industry, but also to compensate (private and state-owned) utilities for their losses resulting from phasing out fossil fuels.

**Renewable energy projects are mainly developed by utilities, both state-owned and private,** and hardly by individuals and communities. Most community energy projects have been halted due to unfavourable policy changes.

**Public support for climate protection and the energy transition is generally high** thanks to strong climate movements and a clear commitment by the government. Nevertheless, there are many conflicts regarding the implementation of certain projects, which – driven by specific government-led tenders – are placed where they are beneficial for the development of the energy system, with less respect for local preferences. As a result, many projects, both in energy production and transmission, are delayed due to protests, but are often built anyway.

### *Market-driven storyline*

*Where are we?* The starting point for the *market-driven* storyline is that the energy transition is possible, but risks becoming too expensive if governments intervene too much in the market (**problem**). The energy transition must be implemented in a cost-effective way so that costs for all Europeans are minimised. This must be done in and through the market, as governments do not have sufficient information to manage the transition in detail.

*Where do we want to go?* To make clean energy technologies competitive, governments are pushing for pricing in externalities of energy generation and setting a clear, enforceable long-term climate target (**solution**). An all-encompassing, sector-spanning carbon price is the main, or only, necessary government intervention: once this is in place, governments **leave it to the market to find efficient solutions**. Citizens primary aim is to have low cost.

**Citizens and municipalities do not play an active role in the energy system of 2050.** The energy system is dominated by larger energy companies, who build mainly large, cost-effective production assets, such as field PV and offshore wind power. There are many market actors, but no citizens and public utilities involved. Hence, the existing centralised system structure remains, with large production units supplying downstream consumers. Moreover, as policies do not specifically target behaviour and restrict individual freedom, the demand for new appliances increases significantly, so that the increase in unit numbers outweighs the efficiency improvements and household demand remains largely constant. Building renovations rates are high, driven by the principle of “Cost-Efficiency First”. However, this leads also to higher rental costs, which partially contribute to an increasing energy poverty. In addition, companies are implementing many measures to increase high demand-side flexibility.

Because this storyline strengthens the individual and their freedom of action, little emphasis is placed on public and communal solutions, so that public transport is hardly expanded and personal mobility

remains car-based, albeit with electric cars; the number of cars on the roads and numbers of flights increase significantly over time.

As **cost-efficiency is the main constraint for the transition for all of Europe**, the transition is planned and implemented with a European scope. This leads to strong dependence on transmission grids, both to supply regions with low resources and high demand, to balance fluctuations in the power system and to improve the efficiency of the European common in terms of interconnections. There are no limitations regarding the cross-border fuels exchange of hydrogen and synthetic fuels.

*How do we get there?* The EU and its Member States are expanding the EU ETS to set **an economy-wide carbon price** to reduce and eventually eliminate carbon emissions. The ETS is the central instrument to procure increasing amounts of renewable energy at the lowest price for all Europeans. There are few or no further climate policies in place: The transition is happening in the market, not with governments.

**Energy companies play a major role in shaping the energy system.** Industry builds large-scale energy projects. The population is hardly involved in the transition, the projects are implemented where they are cheapest and sometimes interfere heavily with the surrounding ecosystems. This leads to high concentration of production or transmission assets in certain locations, which results in resistance and significant delays in the construction of such projects and sometimes the cancellation of individual projects. The climate movements cannot stop the **high regional opposition towards large-scale renewable energy projects**, nor does the government intervene to overcome opposition. The transition is happening in favour of the market.

**Table 2** presents the social storylines and their key features/ variables.

**Table 2:** Three social storylines of the energy transition (RE = renewable energy; EE = energy efficiency).

Storyline features/ variables	People-powered	Government-directed	Market-driven
Summarising description	People drive the transition by becoming individual and collective (co-)owners of RE. People benefit from the transition, which mainly happens regionally. The energy system is characterised by decentralised RE and minimal grids. There is a "Renewable Energy First"-mentality.	The government directs the energy transition, which mainly happens nationally. General public support is high but so is partially local opposition. Society is less involved in the transition. The government's "Energy efficiency first" philosophy decreases energy consumption.	Market actors and new technologies drive the energy transition guided by cost-effectiveness concerns. The transition happens with a continental scope. Society does not play a large role in the energy transition. Local opposition against large-scale projects is high. The energy system is characterised by a centralised generation and transmission.
Problem definition today	Energy system is characterised by fossil-nuclear complex and centralised power structures, and undemocratic energy supply.	Emissions are too high because we use the wrong technologies and have the wrong practices.	Energy transition risks being overly expensive, if governments interfere too strongly with the market.
Solution	Break up existing centralised structures; build driven by and for citizens, cooperatives, municipalities	Reduce emissions by replacing production assets and fuels with carbon-free ones; all while always maintaining security of supply and controlling direction of transition	Governments push for pricing in external effects, set long-term climate target, and then leave it to the market to find efficient solution.
Main decision/ system planning "logic"	Local needs & capacities; regional expansion logic	Security & control; national expansion logic	Cost-effectiveness; European expansion logic

<i>Where do we want to go?</i>			
Energy system 2050	climate-neutral, mainly renewable-energy-based		
<b>Resulting social system design:</b>			
Actor diversity	High diversity with many small and medium size companies, cooperatives, and municipal utilities	Medium diversity with private and public utilities	High market actors (no citizens, no public utilities)
Ownership of renewables: individuals and community energy	High local citizen participation and (co-)ownership, with many prosumers	Public and private utilities as central enactors; bottom-up initiatives and citizen energy is not strongly represented	Private companies dominate ownership of infrastructure
Household's electricity consumption of appliances and lightening	Slight decrease as current trend	High decrease - "EE first"	Constant (market-driven increase of new appliances and use cases)
Energy efficient building renovation	Low renovation rate (RE First)	Very high renovation - "EE first"	High building renovation rate (cost-effective first)
<b>Resulting tech system design:</b>			
Centralisation vs. decentralisation	Decentralised, small units	Mainly centralised, larger units	Centralised, larger units
Storage	Decentralised storage (e.g. batteries) as main balancing option	Grid-scale storage, national transmission	Balancing through European transmission, large-scale storage
Grid infrastructure	Minimised/ no new, regional focus	As much as needed, national focus	Much, European focus
Electricity transmission	Regional transmission, without new transmission	Mostly national, with transmission	European and beyond, with much transmission
Fuel exchange	Mainly autarky	Limited trade	Free trade
Mobility	Shared solutions are common; expansion of public transport; fewer, decarbonised cars; people fly less; synthetic fuels are only used in aviation and shipping	Transport systems change only moderately; expansion public transport; the number of cars on the street remains largely constant; aviation traffic remains constant with pre-COVID 2019 energy demand; synthetic fuels are only used in aviation and shipping	Little emphasis on public and communal solutions; public transport is hardly expanded, and personal mobility remains car-based; flights increase with current trends; synthetic fuels are only used in aviation and shipping
<i>How do we get there? Drivers/ barriers</i>			
Public participation and investments	High public participation and private investments in RE	Just Transition Mechanism has pushed investments; community projects have stopped due to unfavourable policy changes	Transition happens in the market, and industry finances large scale projects
Social movements	Strong climate movement; weak local anti-movements	Strong climate movement; medium to strong local anti-movements	Medium climate movement; strong local anti-movements
RE acceptance: public, local, market	Local and public acceptance is high for small-medium-scale projects; market acceptance is low for small-scale projects	Public high for general transition; local low for large-scale	Local low for large-scale projects; market high for large-scale projects
Opposition against projects	Low against small scale RE, local grids and solutions; no serious delays; high against large-scale and transmission, delays and cancellations	High opposition with significant delays, but few cancellations as governments override opposition	High opposition with significant delays, some cancellations as governments do not interfere to overcome opposition
Climate and energy policy	Ambitious policies, supporting individuals, communities, and smaller enterprises to take ownership of the energy transition	Ambitious national climate and energy policies	Sector-spanning carbon price; few climate policies in place supporting markets, not individuals and communities

(continued table)

## 4.2 QTDIAN quantitative parameters

The second key element of QTDIAN is quantitative parameters. Here, we provide quantifications for six themes, or puzzle pieces, that are based on features of the social storylines. In **section 4.3**, we will then attempt to fit specific qualifications back into the three QTDIAN storylines.

The objective of the QTDIAN quantitative parameters is to provide empirically based quantifications for specific storylines features. We have grouped different features into six QTDIAN themes:

- 1) Socially feasible scaling of energy technologies, addressing the question “how fast can we go with the expansion of renewable energy?”;
- 2) Policy preferences & dynamics, addressing how different policy strategies of countries influence the transition;
- 3) Attitudes towards renewables, presenting people’s opinions and preferences for renewable energy sources;
- 4) Barriers to infrastructural developments, addressing what factors hinder the expansion of onshore wind and grid infrastructure;
- 5) Citizen energy, delivering the status quo and potential for autoproduction (meaning of enterprises their main activity is not energy production as approximation; and
- 6) Private energy demand, tackling three influence factors: building renovation rates, living space, electricity consumption of appliances, development of e-mobility.

The quantifications can be used in the context of the social storylines, but they can also be used independently.

For each of the puzzle pieces, we collected and analysed data sets, and provide data-driven implications of the analysis. The represented qualifications do not necessarily reflect a status-quo of what is available and further data sets could be added in an updated version. The QTDIAN datasets (version 2) are available at ZENODO (Süsser et al., 2022a).

### 4.2.1 Socially feasible scaling of energy technologies

#### 4.2.1.1 Relevance and purpose of the quantification for modelling

Although assumed in many models, transitions are not linear. In the real world, we observe different diffusions of technologies, especially the S-curves described in the literature on innovation and transitions. But how fast can we scale renewable energy technologies? And how fast can we scale down fossil energies? To answer these questions, we looked at how fast countries have installed capacity in the past to draw conclusions about the possible future speeds of scaling up or down energy technologies. This allows us to assess the extent to which current expansion plans are socially acceptable. Additionally, it allows modellers to model more realistic technology diffusion paths, using past rates of change and expansion speeds to set a minimum limit for future speeds.

#### **Research questions related to data**

*Does the speed of technology deployment affect the speed and direction of the energy transition? How fast was electricity generation capacity scaled up in the past, how fast did systems change, and what*

can we say how feasible it is for future developments? And what are the limits of where we could go by the target year (e.g., 2050)?

#### 4.2.1.2 Output data from QTDIAN

- **Available technologies:** Combustible fuels, wind, PV
- **Available geographies:** EU 28 + Albania, Bosnia Herzegovina, Georgia, Iceland, Liechtenstein, Kosova, Moldova, North Montenegro, Montenegro Norway, Serbia, Turkey, Ukraine; 247 countries and areas
- **Available timeframe:** 1990-2019
- **Format:** text files (CSV data format)

#### We provide three types of data:

- 1) The maximum speed of expansion or capacity growth/degradation [GW/year] for the world, for fastest country in the world, for Europe, for the fastest country in Europe. This indicates how fast it has been possible to add new capacity to the power system in the past.
- 2) The maximum rate of change over 5 years [ $\text{MAX}(\text{GW}/\text{year}_t) / (\text{GW}/\text{year}_{t-5})$ ]. We only do this for Europe and the world, as supply chains are rarely purely national. This shows how quickly supply chains can scale when markets demand it.
- 3) The system change per year, for the world countries with the highest capacity growth/decline; for Europe; for the fastest country in Europe. This indicates how quickly it has been possible in the past to change the structure of an existing system.

**Table 3** shows the model input parameters provided by QTDIAN as output.

**Table 3:** Model input parameters on scaling and decline of energy technologies

Model input parameters	Unit of the data	Available geographies	Available time frame	Data source(s)	Data availability
<b>Maximum change rate: Installed combustible capacities</b>	Capacity growth [GW/year]	EU 28+ World countries and areas	1990-2019 1990-2019	<a href="#">Eurostat</a> , 2019 <a href="#">UN</a> , 2021	Open Open
	Maximum change rate over 5 years [ $\text{MAX}(\text{GW}/\text{year}_t) / (\text{GW}/\text{year}_{t-5})$ ]	World countries and areas	2000-2019	<a href="#">IRENA</a> , 2021	Open
	System change per year [% of total system capacity added/year]				
<b>Maximum change rate: Installed wind power capacity (onshore and offshore)</b>	Capacity growth [GW/year]	EU 28 + World countries and areas	1990-2019 1990-2019	<a href="#">Eurostat</a> , 2019 <a href="#">UN</a> , 2021	Open Open
	Maximum change rate over 5 years [ $\text{MAX}(\text{GW}/\text{year}_t) / (\text{GW}/\text{year}_{t-5})$ ]	World countries and areas	2000-2019	<a href="#">IRENA</a> , 2021	Open
	System change per year [% of				

	total system capacity added OR removed/year]				
<b>Maximum change rate: Installed solar PV capacity</b>	Capacity growth [GW/year]	EU 28+ World countries and areas	1990-2019 1990-2019	<a href="#">Eurostat</a> , 2019 <a href="#">UN</a> , 2021	Open Open
	Maximum change rate over 5 years [MAX (GW/year <sub>t</sub> ) / (GW/year <sub>t-5</sub> )]	World countries and areas	2000-2019	<a href="#">IRENA</a> , 2021	Open
	System change per year [% of total system capacity added/year]				

(continued table)

Further information on the data availability, limitations, and analysis can be found in the **Appendix 1**.

#### 4.2.1.3 Findings of the data analysis

##### 4.2.1.3.1 Capacity growth/ decline

###### World

The three countries with the maximum speed of deployment, or capacity growth for solar PV, wind and combustibles are China, the US and India (**Figure 11**). Using the [UN data](#)<sup>6</sup>, we find that

The maximum speed of **wind** deployment, or wind capacity growth for the top three countries is:

China: 34.18 GW/year in the year 2015

USA: 13.40 GW/year in the year 2012

India: 10.39 GW/year in the year 2016

The maximum speed of **solar PV** deployment, or solar capacity growth for the top three countries is:

China: 54.11 GW/year in the year 2017

India: 12.02 GW/year in the year 2017

The US: 11.27 GW/year in the year 2016

The maximum speed of **combustible** deployment, or combustible capacity *growth* for the top three countries is:

China: 92.44 GW/year in the year 2006

India: 56.70 GW/year in the year 2016

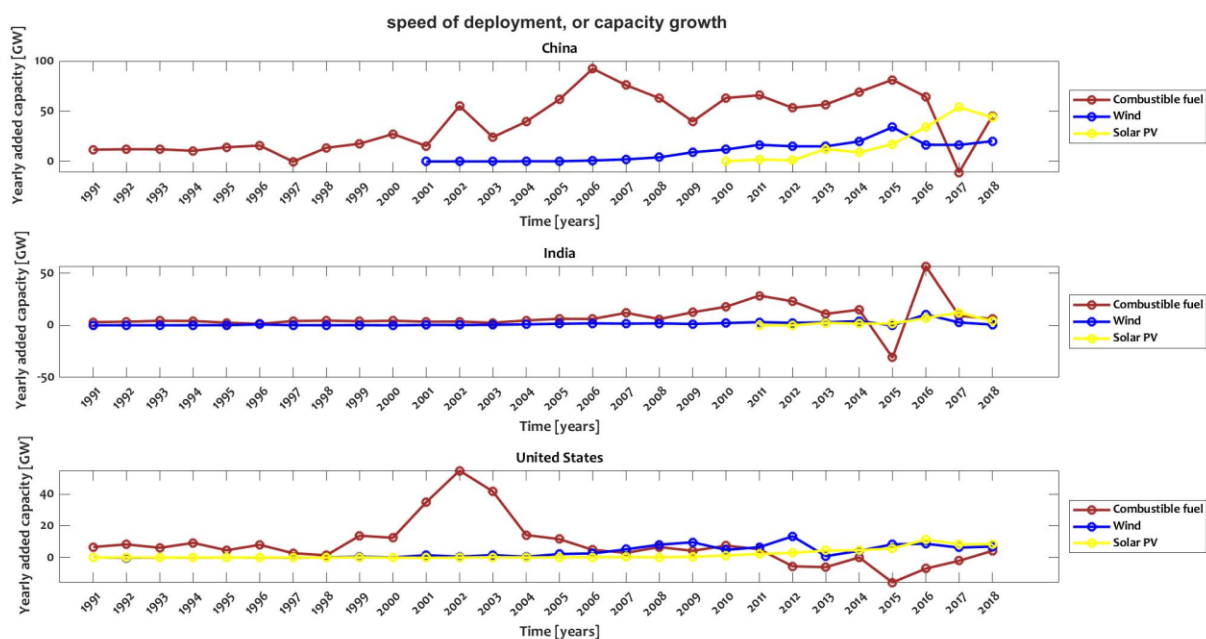
US: 54.81 GW/year in the year 2002

The maximum speed of combustible deployment, or combustible capacity *removal* for the two countries is:

US: 15.68 GW/year in the year 2015

China: 10.79 MW/year in the year 2017

<sup>6</sup> Not all countries/ areas have provided data on wind capacities, and sometimes for different periods (data 1990-2019 is not always available). This holds the same for solar PV and combustible fuel data.



**Figure 11:** China, India, the US capacity growth. Data source: UN, 2021.

**In the US**, in 2012, 13.4 GW of wind capacity was added, and similarly combustible capacity removed. The addition of wind, which is equal to 1.2% of total capacity, is the fastest capacity addition in the US. Starting 2005 the US began to remove/ decommission combustible capacity. The fastest was in 2015 where 15.7 GW was removed, which is about 1.6% of total capacity. Simultaneously in the same year, 5791 MW of solar PV capacity was added as well as 8341 MW of wind capacity.

**In China**, there were high addition of combustible capacities of 92.44 GW of in 2006, and 81.43 GW in 2015. The highest combustible capacity removal/ decommission was in 2017 where 10.79 GW was removed. China started in 2010 to build-up solar capacity; the highest solar capacity addition was in 2017 with 54.11 GW. China started in 2001 to build-up wind capacity; the highest wind capacity addition was in 2015 with 34.18 GW.

**India** removed 30.97 GW of combustible capacity in 2015, while it added 56.7 GW of new combustible capacity just a year later. India started to build-up solar capacity in 2011; the highest solar capacity addition was in 2017 with 12.02 GW. The highest wind capacity addition was 10.39 GW in 2016.

Using [IRENA data](#) (cf. **Table 3**), we derive at slightly different speeds of deployment, or capacity growth/ decline for the world countries.

We find that the maximum speeds of **wind** deployment, or wind capacity growths were:

- China with 34.23 GW/year in 2015
- USA 13.40 GW/year in 2012
- Germany 6.15 GW/year in 2017
- India with 4.15 GW/year in 2017

The maximum speed of solar PV deployments, or solar capacity growths were:

- China with 53.01 GW/year in 2017
- USA 11.27 GW/year in 2016
- Japan 11.27 GW/year in 2018
- Italy 9.54 GW/year in 2010

Figure 12 visualises these developments.

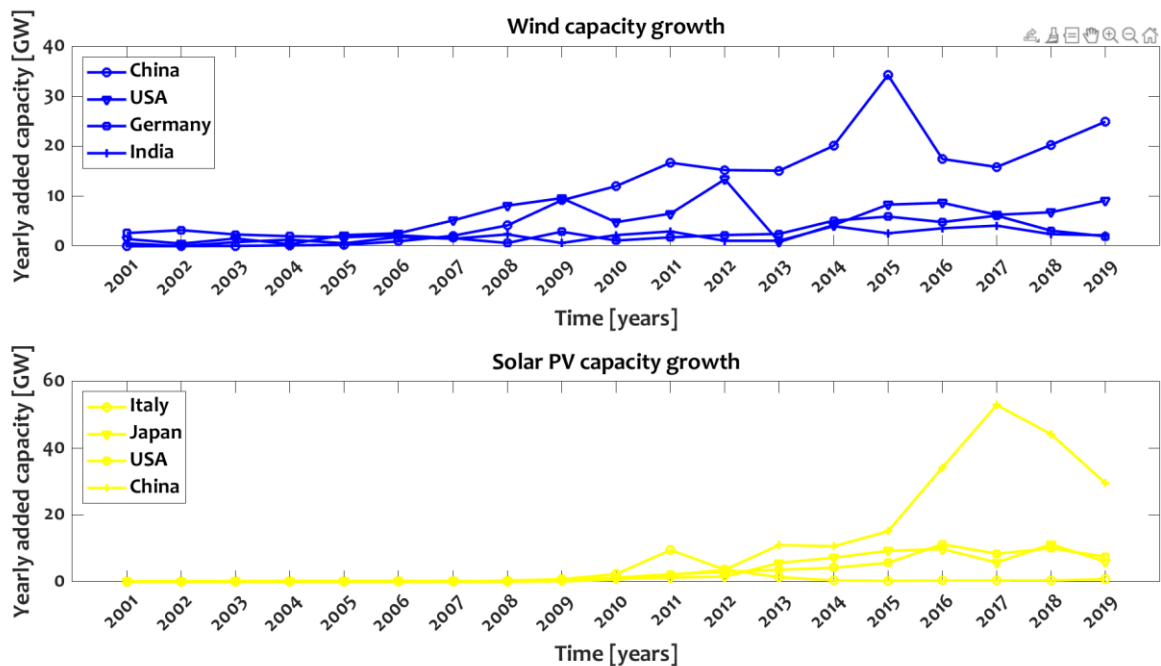
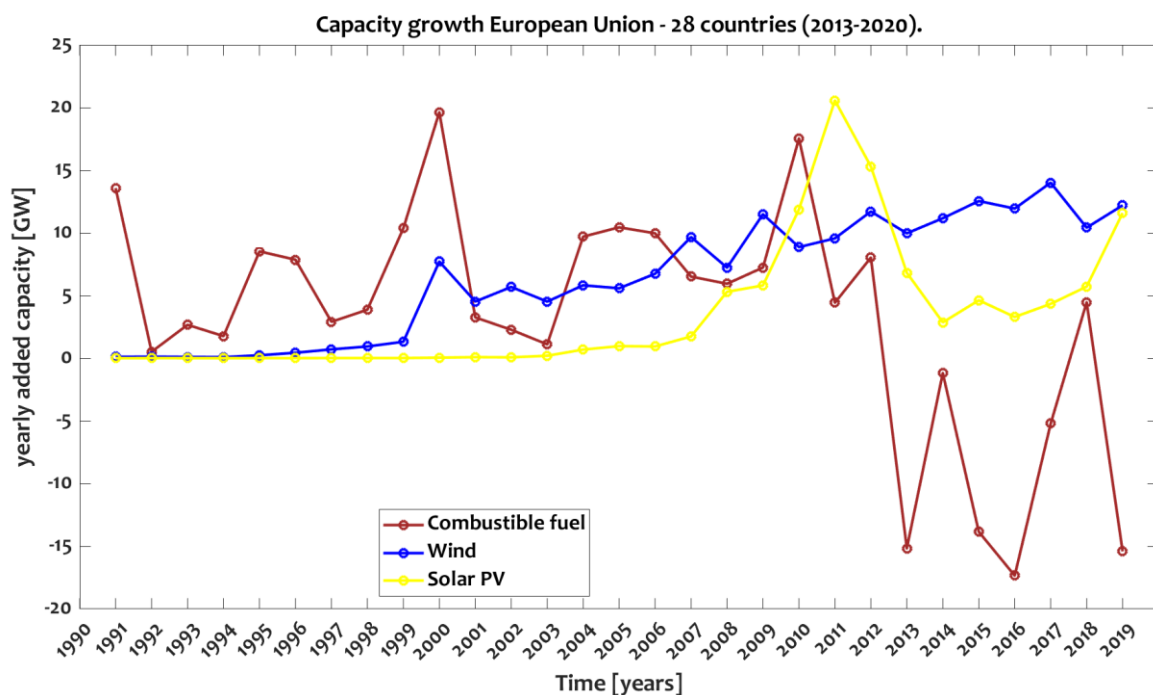


Figure 12: Capacity growth for wind and solar PV, fastest countries. Data source: IRENA, 2021.

### Europe

Figure 13 shows that 20.57 GW of solar PV capacity was added in the EU 28 in 2011, about 2.2% of total capacity, which is the highest (fastest) addition. The fastest addition of wind capacity was 14.01 GW in 2017. Wind has a lower share of capacity addition compared to solar PV. However, wind capacity has a more consistent annual growth/addition of around 1%. The fastest combustible fuels (mainly coal and gas) capacity declines were 15.17 GW in 2013, 17.34 GW in 2016 and 15.41 GW in 2019.



**Figure 13:** Capacity growth/decline EU 28. Data source: IRENA, 2021.

#### Largest capacity growth/ decline in European countries

The fastest growth in **solar PV** capacity was in Italy with 9.54 GW in 2011, followed by Germany with 8.16 GW in 2012 and Spain with 4.1 GW in 2019 (cf. **Figure A 1, Appendix 1**).

The fastest growth of **wind** capacity is recorded in Germany with 6.15 GW in 2017, followed by Ukraine 3.19 GW in 2017 and Spain 3.10 GW in 2007. In addition, Germany recorded high wind capacity growths of 6.10 GW and 6.00 GW in 2000 and 2015, respectively (cf. **Figure A 2, Appendix 1**).

Ukraine had the highest **combustible** capacity *addition* of 31.72 GW in 2017, followed by Germany with combustible capacity *addition* of 31.72 GW in 2017, followed by Germany with combustible capacity *addition* of 15.04 GW in 1991, and Italy with combustible capacity *addition* of 12.12 GW in 2000. The fastest combustible capacity *decline/ removal* is in the United Kingdom with 7.6 GW in 2016, followed by Italy with 6.84 GW in 2015, and Germany 4.08 GW in 2003 (cf. **Figure A 3, Appendix 1**).

#### 4.2.1.3.2 Maximum change rate over 5 years

##### EU 28

Analysing the Eurostat data, we find that for the EU 28, the maximum change rate (growth) of **wind** capacity was 61.11 GW over the five-year period 2014–2019. Furthermore, the maximum change rate (growth) of **solar PV** capacity was 60.37 GW over the five-year period 2008–2013. The maximum change rate (decline) of **combustible fuels** was a 52.74 GW capacity over the five-year period 2012–2017.

## World

Analysing the IRENA data<sup>7</sup>, we find that the maximum change rate (growth) of wind capacity was 272.95 GW over the five-year period 2014–2019, and the maximum change rate (growth) of solar PV capacity was 409.17 GW over the five-year periods 2014–2019.

### 4.2.1.3.3 System change per year

#### Country data China, US and India

We calculated the system change for the top three countries in capacity growths and declines, based on UN data (cf. **Table 3**). We find the fastest speed for wind growth as well as fastest decline of combustibles in China, and the fastest solar growth in India (cf. **Figure A 4, Appendix 1**):

Countries with the fastest speed for wind:

- China with 1.47%
- US with 1.20%
- India with 0.94%

Countries with the fastest speed for solar PV:

- India with 2.78%
- China with 2.76%
- US with 1.00 %

Countries with the fastest decline for combustible fuels:

- China with 3.32%
- India with 3.01%
- US with 1.59%

When calculating the system change for the top three countries in capacity growths and declines, based using UN and IRENA data (see section Capacity growth/ decline), we find that:

Countries with the fastest speed for wind:

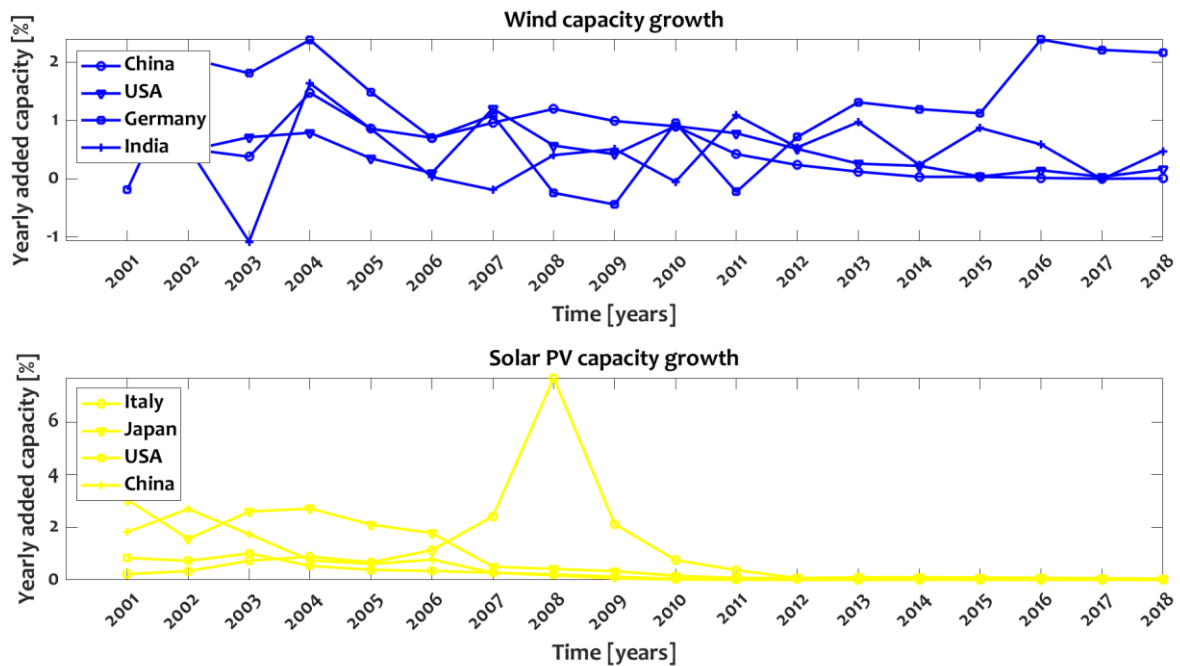
- Germany with 2.38% in 2016
- China with 1.47% in 2004
- US with 1.2% in 2007
- India with 1.63% in 2004

Countries with the fastest speed for solar PV:

- Italy with 7.68% in 2008
- Japan with 3.05% in 20021
- China with 2.69% in 2002
- USA with 1.01 % in 2003

**Figure 14** shows the capacity growths as percentage.

<sup>7</sup> Only data for solar PV and wind are available.



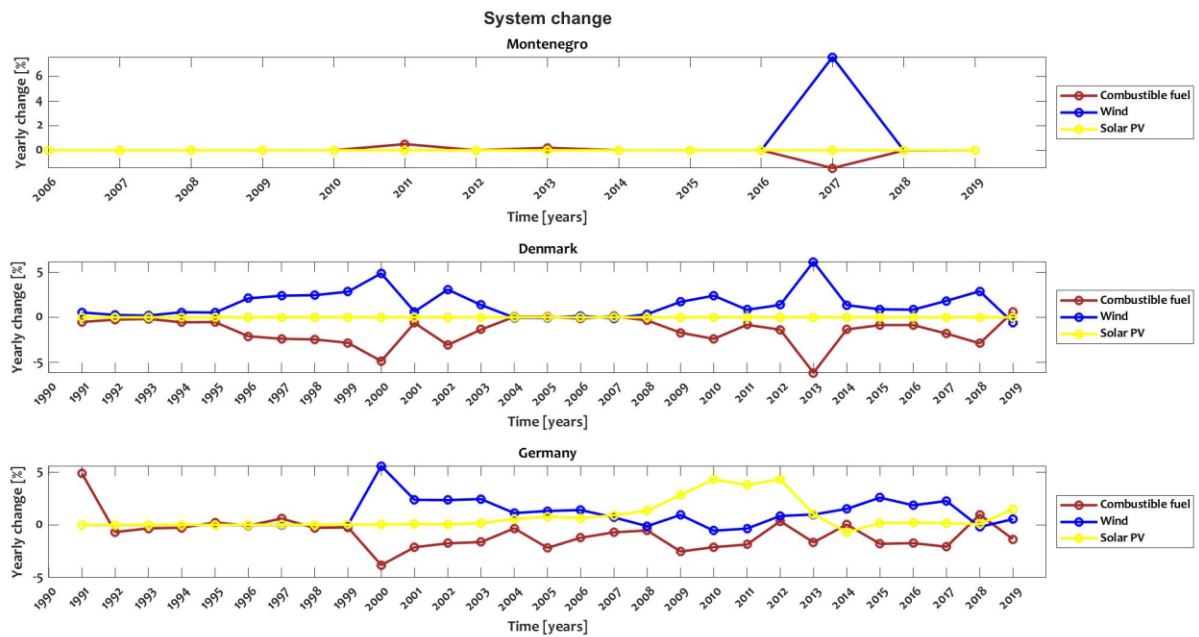
**Figure 14:** Capacity growth as percent, Wind and PV, fastest countries. Data sources: UN and IRENA data.

### Europe

The highest (fastest) addition of solar PV capacity was 2.2% of total capacity in the EU 28 in 2011 (cf. **Figure A 5, Appendix 1**). The fastest wind capacity addition was 1.3% in 2017. In comparison to solar PV, wind experiences a less steep capacity addition. Instead, it has a more consistent yearly growth/ addition of about 1%. The EU has removed 1.9% of combustible capacity in 2019, and before similar capacity percentages in 2013 and 2016 (1.8% each time).

### Fastest country speeds in Europe

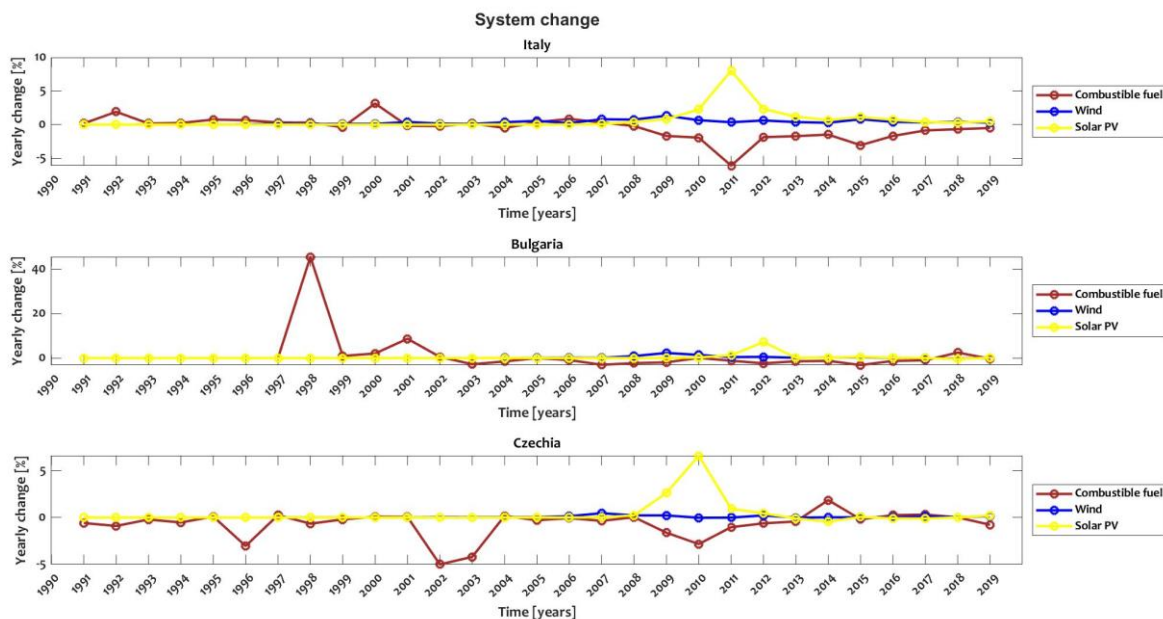
The fastest observed uptake for wind energy was in Montenegro in 2017, with 72 MW or **7.59%** of the total installed capacity – the wind data for the years before 2017 are 0 GW. The second fastest uptake was in Denmark in 2013 with 657 MW or **6.13%** of the total installed capacity. Third fastest uptake was in Germany in 2000 with 6145 MW or **5.59%** (108.88 GW total installed capacity in 2000) – there were no wind installation before 2000 (**Figure 15**).



**Figure 15:** Montenegro, Denmark, and Germany system change. Data sources: UN and IRENA data.

As illustrated in **Figure 16**, the fastest observed uptake for solar PV was in Italy in 2011, with 9,539 MW or **8.0%** of the total installed capacity. The second fastest uptake in Bulgaria in 2012, with 1260 MW, or **7.2%**. The third fastest uptake was in Czechia in 2010, with 859 MW, or **6.6%**.

Maximum system change (decline) in combustible capacity: 20.4% of total installed capacity in 2016 in Luxembourg, 8.9% in 2015 in Lithuania, 8.3% in 2000 in Slovakia (cf. **Figure A 6, Appendix 1**). Maximum system change (growth) in combustible capacity: 58.7% in 2013 in Serbia, and 45.7% in 1998 in Bulgaria.



**Figure 16:** Bulgaria, Czechia, and Italy system change. Data sources: UN and IRENA data.

## 4.2.2 Policy preferences & dynamics

### 4.2.2.1 Relevance and purpose of the quantification for modelling

Current and future political decisions strongly influence the possible energy future. Therefore, the energy system in 2050 will to a large extent be determined by the sum of policy decisions affecting the electricity, heat and transport systems until 2050. As policy decisions are a dynamic process, policy changes are likely to occur. Here we consider different policy preferences and the quantitative variables/input parameters of policy objectives associated with them. We examine policy strategies in the three SENTINEL case studies: the European Union+, Nordic countries and Greece (Stavrakas *et al.*, 2021). For each case, we define a dominant pathway based on the currently existing, implemented policies of the current government. In addition, for the European and Greek case study, we identify a minority pathway describing the energy policy visions and strategies of other organisations, such as civil society actors, that could become the majority policy pathway in the future. This is the same approach as used in the Horizon 2020 project MUSTEC, described in Lilliestam *et al.* (2019) and applied in energy system modelling in Resch *et al.* (2020) and Schöniger *et al.* (2020). However, QTDIAN is applied to different policy cases and expanded for a broader set of technologies and policies.

Secondly, we provide information on current regulations regarding country-specific distance regulations for onshore wind. In addition to density, spacing also influences the acceptance or rejection of wind energy projects (Setton, 2019). Therefore, we have analysed the current regulations on densities. Both factors influence how much land is available for onshore wind development. A similar issue could apply to ground-mounted solar PV installations. However, we found no evidence that countries regulate spacing or sizes per se. However, we do see size limits in some countries' auction systems, and since the tenders are defined, this defines also the maximum size of the projects. In Germany, for example, the size of ground-mounted solar PV installations in tenders is limited to 20 MW (Bundesregierung, 2021).

### Research questions related to data

*How do different policy strategies affect the development of renewable energy? How can we represent policy changes in models, and what are the effects? How do different regulations regarding distances between wind energy plants and settlements influence the wind potential?*

### 4.2.2.2 Output data from QTDIAN

- **Available geographies:** EU, Nordic countries, Greece
- **Format:** text files (CSV data format)
- **We provide two sets of data:**
  - 1) Different policy strategy objectives for the EU, the Nordic countries and Greece. This indicates different policy paths of the countries and allows them to be explored with the models. **Table 4** illustrates the available model input parameters.
  - 2) Regulations for setback distances and densities for wind power. This constrains the available land for the expansion of wind power technologies and allows to investigate whether enough land is available under high societal restrictions.
  - 3) **Table 5** illustrates the available model input parameters.

**Table 4:** Model input parameters for different policy strategies

Model input parameter	Unit of the data by year (2030, 2040 and/ or 2050)	Available geographies
Total GHG reduction targets	Emission reduction in percentage [%]	EU, 5 Nordic countries, Greece
ETS sector reduction targets; Non-ETS sectors emission reduction targets	Percentage [%]	EU, Denmark, Sweden
Renewable energy targets	Percentage in gross final energy consumption Percentage in gross final electricity consumption/ production [%] Percentage in gross final consumption for heating and cooling [%] Percentage in gross final consumption in transport [%]	EU, Denmark, Finland, Sweden, Greece
Installed renewable power capacity	Capacity in GW and %	Greece
Fossil fuel targets/ phase-out	Phase-out year	EU (PAC scenario), Denmark, Finland, Greece
Installed gas power capacity	In GW	Greece
Share of installed electricity capacity	Percentage [%]	Greece
Energy efficiency improvements	Energy intensity in percent compared to forecast [%] Energy consumption in Mtoe	EU, Sweden, Greece
Targeted cumulative energy savings	Mtoe (2021-2030)	Greece
Final energy consumption	Percentage per year [%] OR in Mtoe Percentage of sources [%] OR TWh	EU, Greece, Finland
Heating demand	Percentage [%]	EU
Cross-border interconnection NTC	Percentage of yearly power production [%]	EU
Energy storage: installed capacities	Energy [TWh] and capacity [GW]	Greece
Residential building renovation	Percentage per year [%] OR #	EU, Finland, Greece
Electric mobility	Number of passengers of electric cars OR Percentage of electric cars sold [%] OR Year of stop selling diesel and petroleum cars OR Percentage of renewables [%]  Phase-out date for new fuel-based cars [year]	EU, Denmark, Norway, Greece  EU

**Table 5:** Model input parameters for country specific setback distances

Model input parameter	Unit of the data by year	Available geographies
Regulations/ recommendations on minimum distances onshore wind and housing,	Distance in meters	EU
Regulations on density of wind turbines in municipalities	Density in percent [%]	Greece

Further information on the document analysis can be found in the **Appendix 2**.

### 4.2.2.3 Finding of the document analysis

#### 4.2.2.3.1 Policy strategies

#### European case study

##### Majority pathway

The currently dominant pathway in the EU is defined by the 2030 Climate & Energy Framework, which includes EU-wide targets and policy objectives for the period from 2021 to 2030 (**Table 6**). The EU has set key targets for 2030 in terms of reducing of GHG emissions (from 1990 levels), the share of renewable energy, and improving energy efficiency. In September 2020, the European Commission proposed to raise the GHG reduction targets for 2030, including emission and removals, from 40% to at least 55% compared to 1990<sup>8</sup>. This also requires an update of the other two targets, and the Commission is expected to come forward with a proposal by July 2021, but because it was not published at the time of writing we have not included any details beyond the increased high-level climate target: all other entries reflect the situation in May 2021. The policies implemented to achieve the existing targets are a mix of market pull (e.g., EU Emissions Trading System (ETS)<sup>9</sup>) and market push policies (e.g., NER 300 programme<sup>10</sup>), without policy interference in the market itself. The EU pushes also for market-based support instruments, such as auctions, which have been developed by many countries to accelerate the development of renewable energy.

**Table 6:** Dominant pathway for the EU (European Commission), based on (Lilliestam et al., 2019; V. Stavrakas et al., 2021).

	2030	2050
<b>Total GHG emission reduction target</b>	>55% reduction (GHG-1990) <sup>11</sup>	100% / climate neutrality
<b>ETS sector reduction targets; Non-ETS sectors emission reduction targets</b>	ETS: 43% (GHG-2005), 2.2% per year; Non-ETS: 30% (GHG-2005)	100%
<b>Renewable energy in gross final energy consumption</b>	32% <sup>12</sup>	>2030 and >2040
<b>Renewable energy in gross final consumption in transport</b>	>14%	-60% (GHG-1990); 65% renewables
<b>Energy efficiency improvements: Energy intensity; Translated energy consumption</b>	32.5% (compared to projections of the expected energy use in 2030); final energy consumption of 956 Mtoe and/or primary energy consumption of 1,273 Mtoe in the EU 28 <sup>13</sup>	>2030 and > 2040
<b>Final energy consumption</b>	-26% primary energy (2005); -20% final energy (2005); -0.8% final energy per year (baseline 2020)	-0.8% final energy per year (baseline 2020)
<b>Heating demand</b>		-90% (GHG-1990); Heating with electricity > today
<b>Cross-border interconnection NTC</b>	≥15% of yearly power production	

<sup>8</sup> [https://ec.europa.eu/clima/policies/eu-climate-action/2030\\_ctp\\_en](https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en)

<sup>9</sup> [https://ec.europa.eu/clima/policies/ets\\_en](https://ec.europa.eu/clima/policies/ets_en)

<sup>10</sup> [https://ec.europa.eu/clima/policies/innovation-fund/ner300\\_en](https://ec.europa.eu/clima/policies/innovation-fund/ner300_en)

<sup>11</sup> [https://ec.europa.eu/clima/policies/strategies/2030\\_en](https://ec.europa.eu/clima/policies/strategies/2030_en)

<sup>12</sup> [https://ec.europa.eu/energy/topics/renewable-energy/renewable-energy-directive/overview\\_en](https://ec.europa.eu/energy/topics/renewable-energy/renewable-energy-directive/overview_en)

<sup>13</sup> [https://ec.europa.eu/energy/topics/energy-efficiency/targets-directive-and-rules/eu-targets-energy-efficiency\\_en](https://ec.europa.eu/energy/topics/energy-efficiency/targets-directive-and-rules/eu-targets-energy-efficiency_en)

<b>Residential building renovation</b>	3% per year <sup>14</sup>	
<b>Electric mobility</b>	No sale of new fuel-based cars by 2035 <sup>15</sup>	

(continued table)

In addition to the targets listed in the table, the hydrogen strategy for a climate-neutral Europe states that the share of hydrogen in Europe's energy mix is projected to grow from the current less than 2% to 13-14% by 2050 (European Commission, 2020). Hydrogen is expected to play a key role to decarbonise the industry and heavy transport sectors.

### Minority pathway

The minority pathway we have analysed is the Paris Agreement Compatible (PAC) energy scenario, developed in the framework of the PAC project<sup>16</sup>. The PAC scenario is in line with the EU leaders' commitment to the Paris Agreement. It is guided by three goals: 1) 65% reduction in GHG emissions by 2030; 2) net-zero greenhouse gas emissions by 2040; 3) 100% renewables in Europe by 2040 in all sectors. **Table 7** lists the main quantifications.

**Table 7:** Minority pathway (PAC scenario) for the EU, own analysis of Climate Action Network Europe and European Environmental Bureau (2020) and IEA Sustainable Development Scenario (IEA, 2021).

	2030	2040	2050
<b>Total GHG emission reduction target</b>	65% reduction (GHG-1990)	net-zero	
<b>Renewable energy in gross final energy consumption</b>	>50%	100%	
<b>Fossil fuel targets/ phase-out</b>	coal mostly disappearing from the mix by 2030, fossil gas by 2035	fossil oil products disappear; most nuclear power plants closed	
<b>Energy demand</b>	45% energy savings as compared to PRIMES 2007 projections for both primary and final energy		halving energy demand between 2015 and 2050
<b>Residential renovation</b>	3% per year of which 70% are deep renovations		
<b>Electric mobility</b>	electric vehicles will progressively dominate roads; up to 22% of the private car fleet, 24% of vans, 27% of busses and 10% of trucks are electrified by 2030 (IEA Sustainable Development Scenario, IEA, 2021)	fully electrified private car fleet; >20% reduction in car use; 10% increase in # of passengers per vehicle by 2040 (compared to the baseline)	

In addition to the quantifications in the table, the PAC scenarios defines that heat pumps will progressively dominate buildings, and that synthetic gases and fuels are essential for decarbonising industry and aviation, besides a smaller and declining contribution of sustainably sourced biogas and biomethane.

<sup>14</sup> [https://ec.europa.eu/energy/content/setting-3-target-public-building-renovation\\_en](https://ec.europa.eu/energy/content/setting-3-target-public-building-renovation_en)

<sup>15</sup> [https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal\\_en](https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en)

<sup>16</sup> [www.pac-scenarios.eu](http://www.pac-scenarios.eu). The scenario has been elaborated jointly by the Climate Action Network (CAN) Europe and the European Environmental Bureau (EEB) together with its member organisations and external experts.

## Nordic case study

### Majority pathway

The Nordic countries (Denmark, Finland, Iceland, Norway, and Sweden) established an institutional collaboration in the climate and energy field. They share a common vision of a carbon neutral region expressed in the Declaration on Nordic Carbon Neutrality adopted by the Nordic prime ministers in Helsinki in January 2019 (Nordic Energy Research, 2020). The basis for the majority pathway provides the NECPs and in case of the non-EU members Norway and Iceland the national climate plans. **Tables 8-11** show the quantitative policy targets of the Nordic countries.

Across the Nordic countries decarbonisation has and will continue to happen more quickly in the electricity and heat sectors than in transport and industry (Norden and IEA, 2016). According to the Nordic Carbon-Neutral Scenario, Nordic electricity generation is already 87% carbon-free and is expected to be fully decarbonised by 2045 (ibid.). Wind energy is expected to play an important role in the Nordic countries, as is increased electricity trading. Most of the emission reduction is needed in the transport sector, and therefore many Nordic countries are pushing for fuel switching and modal shift.

**Table 8:** Dominant pathway for Denmark, based on the Danish NECP (Danish Ministry of Climate, Energy and Utilities, 2019)

Denmark	2030	2050
<b>Total GHG emission reduction target</b>	-70% (GHG-1990)	net-zero emissions
<b>Non-ETS sectors emission reduction targets</b>	Non-ETS: 39% (GHG-2005)	
<b>Renewable energy in gross final energy consumption</b>	55%	-
<b>Renewable energy in gross final electricity consumption</b>	>100%	>100%
<b>Renewable energy in gross final consumption for heating and cooling</b>	60% for heating and cooling sector as a whole; at least 80% of district heating consumption is based on energy sources other than coal, oil or gas	
<b>Percentage in gross final consumption for transport</b>	19%	
<b>Lignite in electricity generation</b>	Phased-out by 2030	
<b>Share of renewable electricity consumption*</b>	No technology specific objectives/ targets; >50% wind energy (expected status 2020); further deployment of renewable energy, in particular wind power (two more offshore wind farms by 2030 - ~5 GW, 10 GW offshore wind connected in total, onshore wind)	
<b>Energy demand (expected)</b>	Increase of 1 Mtoe in primary energy consumption; 0,5 Mtoe in final energy consumption (between 2021 and 2030)	
<b>Electric mobility</b>	A stop to sales of all new diesel and petrol cars; increase the electrification of the transport sector	

\*Note: The NECP does not set objectives/ targets for individual technologies to use to achieve the overall and sectorial trajectories. Model-based trajectories are provided by Danish Ministry of Climate, Energy and Utilities (2019, 44pp.).

**Table 9:** Dominant pathway for Finland, based on the Finnish NECP (Ministry of Economic Affairs and Employment, 2019)

Finland	2030	2035
<b>Total GHG emission reduction target</b>	-39% (GHG-2005); electricity and heat production nearly emission free	carbon neutrality
<b>Renewable energy in gross final energy consumption*</b>	>51%	-
<b>Renewable energy in gross final electricity consumption</b>	53%	
<b>Renewable energy in gross final consumption for heating and cooling</b>	61%	
<b>Percentage in gross final consumption for transport</b>	45%	
<b>Renewable energy in gross final consumption in transport</b>	30%	
<b>Lignite, peat and oil in electricity generation</b>	Phase-out by 2029; Half the use of peat by 2030; >50% reduction in domestic use of imported oil	
<b>Final energy consumption</b>	<290 TWh (corresponds to approximately 405 TWh of primary energy consumption)	
<b>Residential building renovation</b>	3% per year	

\*Note: NECP states that the expected total gross final energy consumption per technology is based on WAM projection (see Ministry of Economic Affairs and Employment, 2019, 55pp.).

**Table 10:** Dominant pathway for Sweden, based on the Swedish NECP (The Ministry of Infrastructure, 2020)

Sweden	2020	2030	2040/2045
<b>Total GHG emission reduction target</b>	-	- 70% reduction in emissions in the transport sector (compared to 2010)	Zero-net GHG emission by 2045, then achieve negative emissions, reducing the emissions from activities on Swedish territory to 15% of their 1990 levels
<b>Non-ETS sectors emission reduction targets</b>		Non-ETS: 63% (GHG- 1990)	Non-ETS: 70% (GHG-1990) by 2040
<b>Renewable energy in gross final energy consumption</b>	50%		(indicative trajectory: 65%)
<b>Renewable energy in gross final electricity consumption</b>	-		100% by 2040
<b>Share of renewable energy consumption*</b>		5 GW increase of wind power, and 2 GW solar power are expected between 2017 and 2030	
<b>Energy efficiency improvement: energy intensity</b>		-50% (compared to 2005); expressed as energy supplied in relation to gross domestic product (GDP)	

\*Note: NECP states that Government believes it is more cost-effective to leave it to the market to determine which technologies are used instead of setting specific targets (see The Ministry of Infrastructure, 2020, 20pp.).

**Table 11:** Dominant pathways for Norway and Iceland, based on national climate plans (Ministry for the Environment and Natural Resources, 2018; Norwegian Ministry of Climate and Environment, 2019)

Norway (Norwegian Ministry of Climate and Environment, 2019)	2025/2030	2050
Total GHG emission reduction target	>40% (GHG-1990) by 2030	80-95% (GHG-1990)
Percentage of electric cars sold	30% of passenger cars by 2025	
Iceland	2030	2040
Total GHG emission reduction target	-40-46% (GHG-2005)	carbon neutrality

## Greek case study

### Majority pathway

The current majority pathway is based on the NECP and the Long-term strategy 2050, which are the Greek government's strategic plans for climate and energy issues. Objectives of the plans have been quantified and are represented in **Table 12**. These objectives are more ambitious than the ones outlined in the draft proposal. This currently dominant pathway followed a *government-directed* logic, even though the influence of market actors has become much stronger in recent years. The role of the government was especially strong by phasing-out coal before consulting with the industry or science (Süsser et al., 2021a). The report emphasised the role of the market by stating that a framework for the sustainable development of the national economy will be established. The role of citizen-driven initiatives is reflected by the objective to promote renewable energy systems in buildings and dispersed PV production, through autoproduction and net metering schemes.

**Table 12:** Dominant pathway for Greece based on Stavrakas et al. (2021), according to NECP (HELLENIC REPUBLIC Ministry of the Environment and Energy, 2019) and Long-term strategy 2050

	2030	2050
Total GHG emission reduction target	-43% relative to 1990 (-56% relative to 2005)	-74.7% relative to 1990
Renewable energy in gross final energy consumption	>35%	67.6%
Renewable energy in gross final electricity consumption/production	>60%	84% of the total electricity generation
Renewable energy in gross final consumption heating and cooling	42.5%	>2030
Renewable energy in gross final consumption for Transport	19%	>2030
Installed renewable energy capacity	19 GW Hydro: 3.9 GW Wind: 7 GW PV: 7.7 GW	26 GW Wind: 10.2 GW (including 0.4 GW of offshore wind) PV: 11.2 GW Hydro: 3.9
Installed gas power capacity	6.9 GW	6.5 GW
Lignite in electricity Generation	0%, phased out by 2025 <sup>17</sup>	-
Energy efficiency improvements: Energy intensity	>38% decrease in energy intensity (compared to the forecast on final energy consumption by 2030 and to achieve lower final energy consumption in	

<sup>17</sup> <https://www.euractiv.com/section/climate-environment/news/greece-confirms-last-coal-plant-will-be-shut-in-2025/>

	2030 compared to that in 2017)	
<b>Targeted energy savings</b>	leading to energy savings of 7.3 Mtoe (in the period of 2021– 2030)	-
<b>Final energy consumption</b>	16.1– 16.5 Mtoe, primary energy consumption: 20.5 Mtoe; Mix: Electricity: 39.1% Bioenergy: 19.3% Natural gas: 15.1% Petroleum products: 9.7% Solar energy: 8.4% Renewables in the form of heat pumps: 7.5% District heating: 0.9%	Primary energy consumption: 16.1 Mtoe; Mix: Electricity: 58.9% Natural gas: 21.7% Bioenergy: 9.9% Renewables in form of heat pumps: 8.6% District heating: 0.7% Petroleum products and fossil fuels: 0.2%
<b>Energy storage: installed capacities</b>	2.2 TWh (pumped hydro, battery energy storage systems (BESS), and hydrogen); installed power capacities equal to almost 1.6 GW for pumped hydro, 1.2 GW of BESS and small shares of hydrogen	8.2 TWh; installed power capacities equal to 1.7 GW of pumped hydro, 2.6 GW of BESS and 0.4 GW of hydrogen
<b>Residential building renovation</b>	600,000 houses; 1.28% annual renovation rate	856,000 houses, 1.24% annual renovation rate
<b>Electric mobility</b>	278,254 electric passenger cars; electricity has a 2% share in total energy consumption	-

(continued table)

#### *Minority pathway*

For Greece, we found a criticism from the civil society perspective, which gives indication for an alternative pathway. A report by the CAN Europe and ZERO (2020) states opportunities coming with the NECP, but also highlights specific gaps in the current Greek NECP. One main criticism constitutes the replacement of lignite with **fossil gas**. According to the current plan, gas will make around a third of the electricity mix in 2030 (cf. **Table 22**). Furthermore, the NECP lacks an updated **spatial plan for renewables**, protecting Greece's rich biodiversity. CAN Europe and ZERO (2020) state that "resistance to new wind power is escalating both in local communities as well as environmental groups". Hence, Greece might fail to produce two-thirds of its electricity by renewables in 2030, resulting in skyrocketing of fossil gas (ibid.). We calculated an electricity mix without natural gas by 2050 (cf. **Table 22**). Moreover, the CAN Europe and ZERO (2020) demand for more ambitious objectives for GHG reductions in the **transport sector**. According to the NECP, CO<sub>2</sub> emissions from the transport sector are 18.1 Mt CO<sub>2</sub> in 2020 and are expected to be 17.2 Mt CO<sub>2</sub> in 2030. Lastly, they state that the capacity goal for **storage** is insufficient (cf. **Table 12**).

#### *4.2.2.3.2 Setback distances and density regulations onshore wind*

There is no EU-wide regulation for setback distances. The minimum distances vary from one Member State to another, in some there are none. In addition, minimum distances are subject to change in some

countries. Some countries set minimum distances based on noise limits, others based on turbine height. In cases where no explicit distance is specified, a 2018 Joint Research Centre (JRC) report by Dalla-Longa et al. (2018) suggests a minimum distance from settlements of 500 metres for large wind turbines and 120 metres for small turbines (with a threshold of 45 dB sound pressure at the building wall), and a distance of 700 metres for large turbines and 200 metres for small turbines if the sound level is reduced to a maximum of 40 dB. The JRC assumes these distances for the JRC-EU-TIMES model (Dalla-Longa et al., 2018). In addition, only in Greece have we found that maximum densities for wind farm coverage apply to municipal areas, ranging from 4% in tourism development regions to 8% in wind priority areas. Detailed information on country distances and density restrictions, as well as the recommendations from the JRC model, can be found in **Table 13**.

**Table 13:** Country setback distances and density restrictions, and JRC model recommendations

Country	Distance between wind turbines and settlements	Source
<b>Albania</b>	No information found in literature. JRC recommendation: 500 meters for the large wind turbines and 120 meters for small wind turbines	Dalla-Longa et al., 2018
<b>Austria</b> - <b>Niederösterreich</b> - <b>Oberösterreich</b> - <b>Burgenland</b> <b>Steiermark</b>	1,200 meters 800 meters 1,000 meters 1,000 meters	Dalla-Longa et al., 2018
<b>Belgium</b> - <b>Flanders</b> - <b>Wallonia</b>  - <b>Brussel</b>	at least 3 times the rotor diameter 400m, or 4 times the total height of the wind turbine Not permitted at all	Dalla-Longa et al., 2018
<b>Bosnia and Herzegovina</b>	No information found in literature. JRC recommendation: 500 meters for the large wind turbines and 120 meters for small wind turbines	Dalla-Longa et al., 2018
<b>Bulgaria</b>	No information found in literature. JRC recommendation: 500 meters for the large wind turbines and 120 meters for small wind turbines	Dalla-Longa et al., 2018
<b>Croatia</b>	Legislation suggests 45db noise limit, minimum of existing installations 350m (Noise Act, national legislation); JRC recommends using 500 meters.	Dalla-Longa et al., 2018
<b>Cyprus</b>	Differences apply between locations. JRC recommendation: 850 meters	Dalla-Longa et al., 2018
<b>Czech Republic</b>	Fulfilment of "hygienic limits of noise"; JRC recommendation: 500 m for the large wind turbines and 120 m for small wind turbines	Dalla-Longa et al., 2018
<b>Denmark</b>	4 times the turbine height; JRC recommendation: 500 meters for the large wind turbines and 120 meters for small wind turbines	Ministry of Environment of Denmark <sup>18</sup> Dalla-Longa et al., 2018

<sup>18</sup> [https://eng.mst.dk/air-noise-waste/noise/wind-turbines/wind-turbine-regulations/#:~:text=Approval%20of%20wind%20turbine%20plans&text=The%20minimum%20distance%20to%20a,Agency's%20website%20\(in%20Danish\)](https://eng.mst.dk/air-noise-waste/noise/wind-turbines/wind-turbine-regulations/#:~:text=Approval%20of%20wind%20turbine%20plans&text=The%20minimum%20distance%20to%20a,Agency's%20website%20(in%20Danish))

<b>Estonia</b>	1000-2000 meters; JRC recommendation: 1000 meters	Dalla-Longa et al., 2018
<b>Finland</b>	1000-2000 meters; JRC recommendation: 1000 meters	Dalla-Longa et al., 2018
<b>France</b>	500 meters residential areas, and 300 meters from nuclear installations	Dalla-Longa et al., 2018
<b>Germany</b>	Differences between Federal States: from case-to-case to 10 times tower height; JRC recommendation: 500 meters	Fachagentur Windenergie, 2021 <sup>19</sup>
<b>Greece</b>	minimum distance from cities and settlements with more than 2,000 inhabitants should be 1,000 m; traditional settlements should be at least 1,500 m away from wind turbines; <2,000 inhabitants' settlements as well as monasteries must have a minimum distance of a 500 meters; minimum level of noise should not exceed 45 dB; JRC recommendation: 500 meters	Dalla-Longa et al., 2018
<b>Hungary</b>	1000-2000 meters; JRC recommendation: 1000 meters	OpenGov, 2021 <sup>20</sup> Dalla-Longa et al., 2018
<b>Iceland</b>	No information found in literature; JRC recommendation: 500 meters for the large wind turbines and 120 meters for small wind turbines	Dalla-Longa et al., 2018
<b>Ireland</b>	40 dB and 500 meters	Dalla-Longa et al., 2018
<b>Italy</b>	200 meters from single dwelling; 6 times tip height from towns (~700 meters); JRC recommendation: 750 meters for the large wind turbines and 120 meters for small wind turbines	Dalla-Longa et al., 2018
<b>Kosovo</b>	No information found in literature; JRC recommendation: 500 meters for the large wind turbines and 120 meters for small wind turbines	Dalla-Longa et al., 2018
<b>Latvia</b>	40-45 dB during the night; JRC recommendation: 500 meters	Dalla-Longa et al., 2018
<b>Lithuania</b>	<45 dB during night, shadow coverage should be less than 30h/year; JRC recommendation: 500 meters for the large wind turbines and 120 meters for small wind turbines	Dalla-Longa et al., 2018
<b>Luxembourg</b>	No information found in literature; JRC recommendation: 500 meters for the large wind turbines and 120 meters for small wind turbines	Dalla-Longa et al., 2018
<b>Malta</b>	No information found in literature; JRC recommendation: 500 meters for the large wind turbines and 120 meters for small wind turbines	Dalla-Longa et al., 2018
<b>Montenegro</b>	No information found in literature;	Dalla-Longa et al., 2018

<sup>19</sup> [https://www.fachagentur-windenergie.de/fileadmin/files/PlanungGenehmigung/FA\\_Wind\\_Abstandsempfehlungen\\_Laender.pdf](https://www.fachagentur-windenergie.de/fileadmin/files/PlanungGenehmigung/FA_Wind_Abstandsempfehlungen_Laender.pdf)

<sup>20</sup> <http://www.opengov.gr/minenv/?p=10255>

	JRC recommendation: 500 meters for the large wind turbines and 120 meters for small wind turbines	
<b>Netherlands</b>	4 times hub height (~400 meters); JRC recommendation: 400 meters	Dalla-Longa et al., 2018
<b>Norway</b>	No information found in literature; JRC recommendation: 500 meters for the large wind turbines and 120 meters for small wind turbines	Dalla-Longa et al., 2018
<b>Poland</b>	10 times total height of the wind turbine including blades; JRC recommendation: 1250 meters for the large wind turbines and 550 meters for small wind turbines	Dalla-Longa et al., 2018
<b>Portugal</b>	Noise regulation ~ 400 meters	Dalla-Longa et al., 2018
<b>Romania</b>	500 meters	Dalla-Longa et al., 2018
<b>Serbia</b>	No information found in literature; JRC recommendation: 500 meters for the large wind turbines and 120 meters for small wind turbines	Dalla-Longa et al., 2018
<b>Slovakia</b>	No information found in literature; JRC recommendation: 500 meters for the large wind turbines and 120 meters for small wind turbines	Dalla-Longa et al., 2018
<b>Slovenia</b>	JRC recommendation: 500 meters	Dalla-Longa et al., 2018
<b>Spain</b>	500-1000 meters	Dalla-Longa et al., 2018
<b>Sweden</b>	1000 meters to urban areas and 500 meters to isolated houses	Dalla-Longa et al., 2018
<b>Switzerland</b>	No information found in literature; JRC recommendation: 500 meters for the large wind turbines and 120 meters for small wind turbines	Dalla-Longa et al., 2018
<b>UK</b> - <b>England</b>  - <b>Wales</b> - <b>Scotland</b> - <b>Northern Ireland</b>	None; several legislative attempts to introduce an England-wide separation distance did not pass through all of the stages in Parliament to become law (range between 700 meters to 10 times the turbine height and even 2 km; unclear which one applies) 500 meters Local recommendation 2000 meters 10 times rotor diameter to occupied property (with a minimum distance of not less than 500 meters)	Dalla-Longa et al., 2018
<b>Country</b>	<b>Density restriction for onshore wind</b>	
<b>Greece</b>	<i>in wind priority regions of the mainland</i> : maximum permissible wind farms land coverage rate for a municipality area cannot exceed 8% of the municipality area; <i>high tourism areas</i> : maximum allowable land coverage rate from wind farms cannot exceed 4% of the municipality area; <i>wind suitable regions of the mainland</i> (i.e., the regions not included in wind priority regions): maximum	OpenGov, 2021 <sup>21</sup> Dalla-Longa et al., 2018

<sup>21</sup> <http://www.opengov.gr/minenv/?p=10255>

	permissible wind farms land coverage rate cannot exceed 5% of the municipality area	
--	---	--

(continued table)

#### 4.2.3 Citizens' attitudes towards renewable energy

##### 4.2.3.1 Relevance and purpose of the quantification for modelling

The issue of social acceptance of the energy transition is increasingly in the focus of public and policy debates. Many research papers have highlighted the importance of understanding public opinions, preferences, and feelings, as well as the different influencing factors it (Boudet, 2019; Devine-Wright, 2007; Devine-Wright and Howes, 2010; Fast, 2013; Wüstenhagen et al., 2007). This is because citizens acceptance and support can influence the diffusion of technologies and development of new infrastructure projects, especially when they take place where people live. That leads to several open questions, such as: Which renewable energy sources do people prefer? Which renewable energy technologies do they support, and which do they oppose? Based on these relevant questions, the further design of the energy system could be built.

##### **Research questions related to data**

*What would future renewable energy landscapes look like if they are based on people's preferences?  
How does the deployment of (regionally, nationally) preferred renewable energy technologies affect potential and total costs?*

##### 4.2.3.2 Output data from QTDIAN

- **Available geographies:** Germany
- **Available timeframe:** 2017-2019
- **Format:** text files (CSV data format)
- **We provide two types of data:**
  - 1) Percentage of people who support or oppose different renewable energy technologies. This indicates which renewable energy sources are preferred by citizens in Germany and thus gives an indication of which should be further developed.
  - 2) Percentage of people who (dis)like different renewable energy technologies in their backyard, both for people who have installed such technologies and for people who have no experience with such technologies in their neighbourhood. This indicates whether people support renewable energy in their neighbourhood at all and which technologies they prefer.

The model input parameters are summarised in **Table 14**.

**Table 14:** Model input parameters for people's attitudes for renewable energy

Model input parameter	Unit of the data	Available geographies	Available timeframe	Data source(s)	Availability
Personal stance about different renewable technologies	Percentage who support, or reject [%]	Germany	2017-2019	Renn et al., 2020 Wolf, 2020	Open
Opinion about renewables in people's backyard	Percentage who would like it, not like it, without previous experience, and with existing installations [%]	Germany	2019-2020	Agency for Renewable Energy (Agentur für Erneuerbare Energien), survey by YouGov	On request

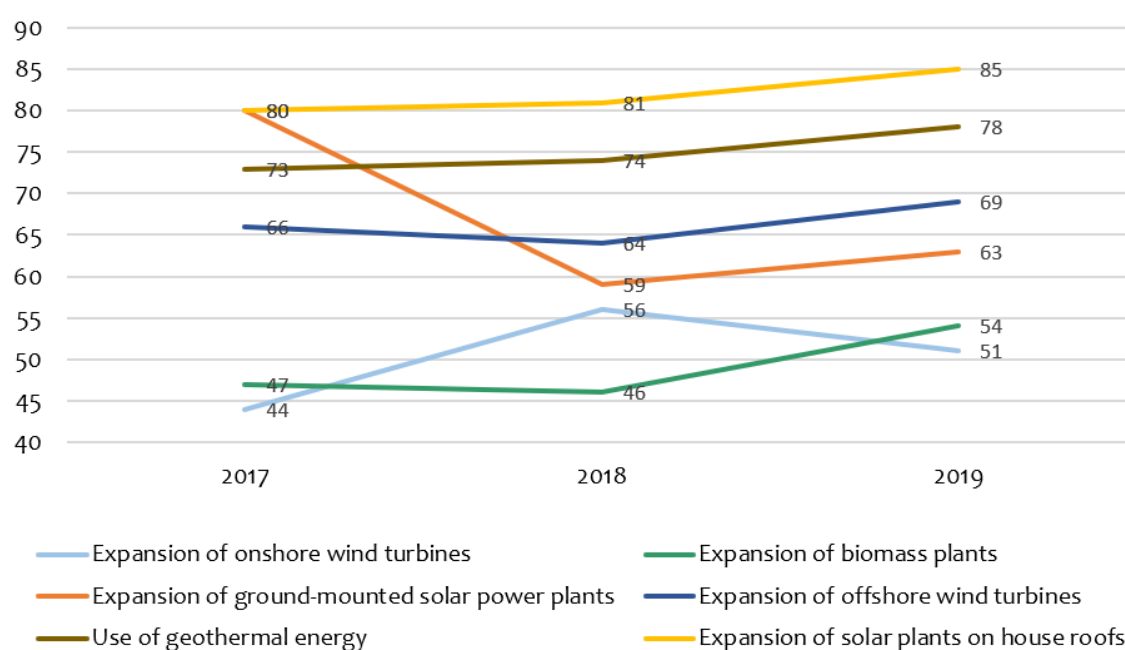
Further information on the data availability, limitations, and analysis can be found in the **Appendix 3**.

#### 4.2.3.3 Findings of the data analysis

##### 4.2.3.3.1 Support or opposition towards renewable energy technologies

Different renewable energy technologies have a large support among the German population. Strongest support has the further expansion/ use of solar energy on roofs and geothermal energy (**Figure A 8, Appendix 3**). The survey results from 2017-2019 show that the agreement for renewable energy is increasing, except a decline for onshore wind in 2019, and a strong decline for ground-mounted solar energy after 2017 (**Figure 17**).

Personal agreement for expansion/ use of certain technologies [in %]



**Figure 17:** Personal agreement for the expansion/ use of certain technologies, respondents who answered 4 or 5 (strong agreement), surveys 2017-2019, Germany. Data source: Wolf (2020).

#### 4.2.3.3.2 Citizen opinions about renewable energy “in their backyard”

The support for renewable energy is also high in and near densely populated areas. If citizens have already experience with installed technologies in their neighbourhood, the support is even higher (**Figure A 9, Appendix 3**). Differences in the support could influence the future design of the energy system, with highest priority given to solar energy systems.

### 4.2.4 Barriers to infrastructure developments

#### 4.2.4.1 Relevance and purpose of the quantification for modelling

The installation of energy infrastructure, especially wind turbines and power grids, leads to various social acceptance issues, related to health concerns, noise, landscape aesthetics, and local ownership (Bolwig et al., 2020; Ceglarz et al., 2017; Cohen et al., 2014). Public opposition to energy developments has been recognised as a serious issue that cannot be ignored. “The current trend, in which nearly every energy technology is disputed and its use or deployment delayed, raises serious problems for investors and puts energy system changes at risk”, states the Energy Roadmap 2020 (European Commission, 2011). Resistance to infrastructural development can constrain the diffusion of technologies and slow down the energy transition overall. Here we look at current barriers to onshore wind energy and grid infrastructure projects and analyse how big a problem these barriers are in terms of the percentage and duration of observed delays. Consideration of these aspects is essential to get an empirical understanding of energy infrastructure development.

#### Research questions related to data

*How does local opposition against renewable energy projects and energy infrastructure projects affect the speed and direction of the overall transition?*

#### 4.2.4.2 Output data from QTDIAN

- **Available technologies:** onshore wind, grid development (transmission and storage)
- **Format:** text files (CSV data format)
- **We provide four types of data:**
  - 1) The realisation duration for onshore wind power developments in Germany. This indicates how fast projects can be realised from granting of the immission control permit to commissioning.
  - 2) The project litigation and duration of proceedings for onshore wind power developments in Germany. This indicates to what extend planned projects cannot be implemented as planned due to local opposition, nature conversation, and other reasons, and hence, what delays they cause for the diffusion of wind energy.
  - 3) Total number of transmission and storage projects expected to be commissioned, and total length (km) of projects and storage capacity (GWh) in Europe (EU28). This indicates the magnitude of the expected grid development over the next centuries.
  - 4) The percentage and duration of grid development projects delayed in Europe (EU28). This indicates to what extend grid development are delayed due to environmental problem, public opposition, and other reasons, and hence, when projects will come into place.

The model input parameters are summarised in **Table 15**.

**Table 15:** Model input parameters for the development of onshore wind and grid development projects

Model input parameter	Unit of the data	Available geographies	Data source(s)	Availability
<b>Onshore wind power development:</b> Realisation duration, project litigation and duration of proceedings	Average realisation time from granting of the immission control permit to commissioning [months]	Germany	Fachagentur Windenergie und Land, <a href="#">Marktstammdatenregister</a>	On request
	Percentage of projects with litigation [%], and average duration of proceedings in months	Germany	Fachagentur Windenergie an Land (Quentin, 2019)	On request
<b>Grid development</b> (transmission and storage): expected amount/capacity; project delays	Total number of projects expected to be commissioned, and total length (km) of projects and storage capacity (GWh), respectively	EU 28	<a href="#">ENTSO-E TYNDP 2020 Projects Sheets, 2020</a>	Open
	Percentage of projects delayed [%]		<a href="#">ACER list of projects of common interest (PCI)</a>	
	Delays in months			

Further information on the data availability, limitations, and analysis can be found in the **Appendix 4**.

#### 4.2.4.3 Findings of the data analysis

##### 4.2.4.3.1 Wind energy development

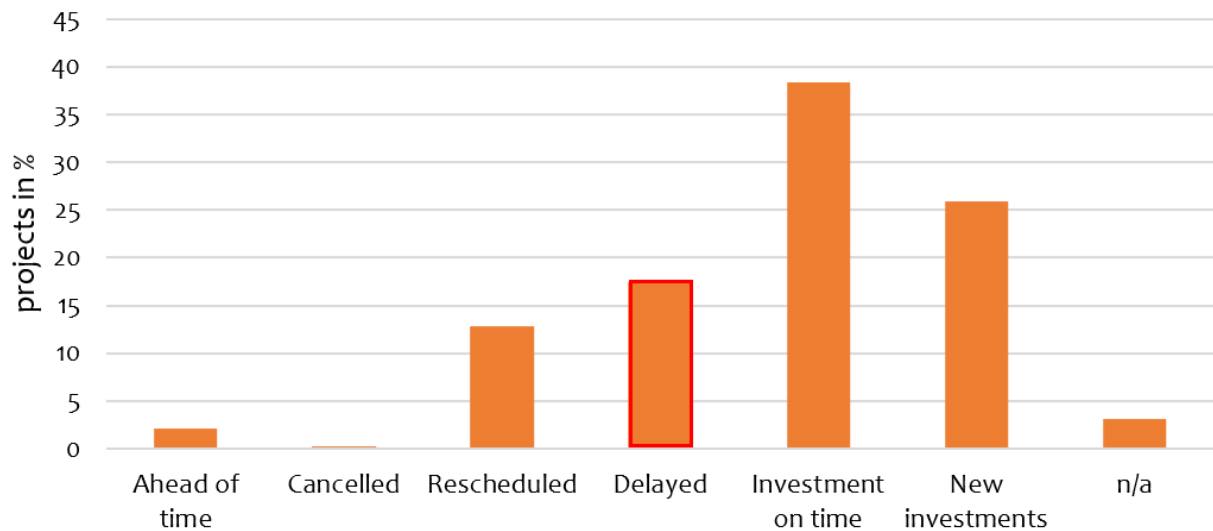
The average realisation duration – from the granting of the immission control permit to commissioning – for wind energy projects is increasing in Germany. In 2020, the **realisation duration was 24.5 months**, in 2015 it was only 12.8 months (cf. **Figure A 10, Appendix 4**). Reasons for this include the increasing complexity in technical and bureaucratic issues.

An industry survey of onshore wind projects (status May 2019) found that **~20% of projects were litigated in approval process** (228/1080 projects). This presents 20% of the total capacity to be installed (cf. **Table A 1, Appendix 4**). The average duration of proceedings (delay) considered across all 325 installations sued (approved and in operation), was 21.6 months at the end of May 2019 (Quentin, 2019). Most frequent litigation groups are environment and nature protection groups, private individuals, citizen initiatives, and municipalities of location (Quentin, 2019).

#### 4.2.4.3.2 Grid development – transmission: expected projects, project delays, cancellation

According to the Ten-Year Network Development Plan (TYNDP) 2020 (ENTSO-E, 2021a), over 300 transmission projects are expected to be commissioned<sup>22</sup> by 2040 with a length of about 45,000 km. Most of the projects fall into the time-period from 2021-2025 (cf. **Figure A 11, Appendix 4**); however, new projects may be commissioned later.

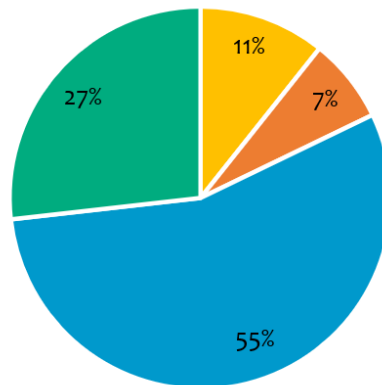
Currently, **17% of TYNDP transmission investments are delayed** (65/321 projects), further 13% have been rescheduled, as illustrated in **Figure 18**. Without consideration of new investments even 24% are delayed. If only AC/DC transmission lines are considered, 28% of the projects are delayed.



**Figure 18:** Progress of transmission investments since TYNDP 2018, n = 321 projects. Data source: ENTSO-E, 2021a.

According to ACER (2020), “the duration of the reported delays varies significantly between the electricity projects (from 3 months up to 4 years). The **average delay is about 17 months.**” Fifty-five percent of the projects are delayed in the permitting phase (56/238 projects in the TYNDP 2020) (**Figure 19**), where local opposition events occur. The TYNDP of 2012 stated that “there has been material delay to the delivery of one third of the investments, mostly because of **social resistance** and longer than initially expected permitting procedures [...]” (ENTSO-E, 2012). In addition, one project was listed as cancelled in the TYNDP 2020. It is likely that there are other projects, but these have not been reported by the transmission companies.

<sup>22</sup> based on the year of commissioning provided by project promoters



Project delays during:

■ Consideration ■ Planning but not yet permitting ■ Permitting ■ Construction

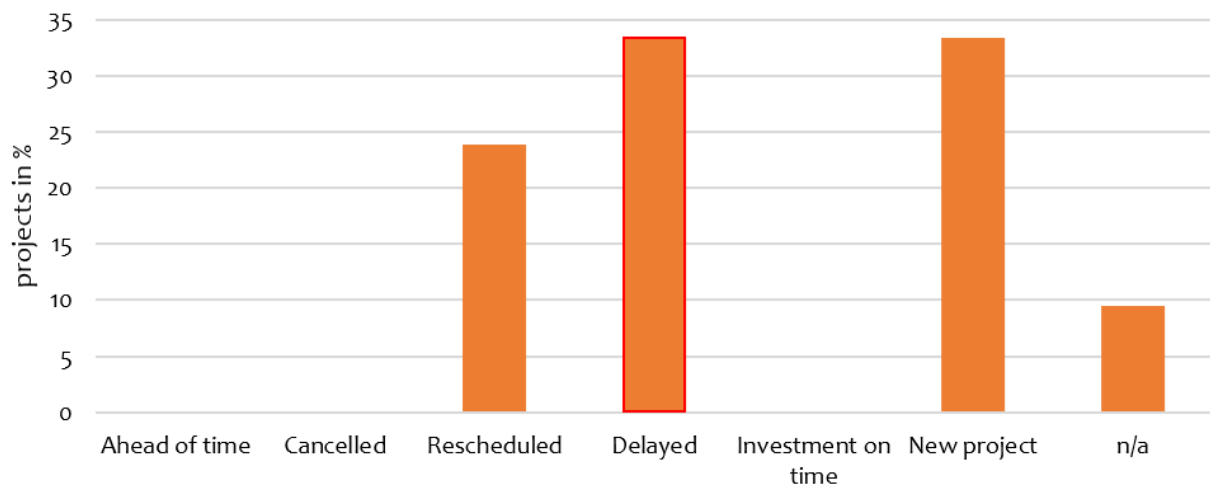
**Figure 19:** Delays of transmission projects per project phase. n = 56 projects. Data source: ENTSO-E, 2021a.

Comparison to other data sources:

- Degel et al. (2016) analysed the resistance and engagement rate in 19 affected districts of the grid expansion of “EnLAG plan 1-6” and “BBGIG plan 8” in Germany, and they found high resistance and average engagement in 6 districts, leading to average delays of about 6 years, and similar resistance but higher engagement in 12 districts, leading to average delays of 4 years.

#### 4.2.4.3.3 Grid development – storage: expected storage capacity, project delays

According to TYNDP 2020 (ENTSO-E, 2021a), 26 storage projects are expected to be commissioned by 2036, with a storage capacity of 29,000 GWh (**Figure A 12, Appendix 4**). New projects are likely commissioned later. As illustrated in **Figure 20**, 33% of TYNDP storage projects are delayed (7/21 projects), further 24% have been rescheduled. Five out of these 7 projects are delayed in the permitting phase.



**Figure 20:** Progress of storage investments since TYNDP 2018, n = 21 projects. Data source: ENTSO-E, 2021a.

## 4.2.5 Citizen energy

### 4.2.5.1 Relevance and purpose of the quantification for modelling

Citizen and community energy have led to increased local acceptance of renewable energy, and given citizens the opportunity to benefit from local renewable energy generation (Rogers et al., 2008; Süsser and Kannen, 2017; Walker et al., 2014). The energy transition has created a new generation of actors as active producers of renewable electricity – an important social trend (Martin et al., 2020). Recent energy policies, such as the EU Energy Union Strategy (COM/2015/080) and the recast of the Renewable Energy Directive 2018/ 2001, recognise the role of citizens in the energy transition. Accordingly, citizens must be empowered to take the energy transition into their own hands, be it through self-production or within the framework of citizen energy projects. Citizen participation is an important aspect to consider, as it influences the future design of the energy system towards more decentralised renewable energy. However, it is not clear what the status quo of the citizen energy is, and what are its development potentials?

#### Research questions related to data

*How does ownership affect the system design? What is the estimated potential of citizen produced solar PV?*

### 4.2.5.2 Output data from QTDIAN

- **Format:** text files (CSV data format)
- **We provide two types of data:**
  - 1) Electricity production capacity by autoproducers, and the percentage of autoproducers, for different renewable energy sources. This indicates how much of the installed capacity is in hands of enterprises which produce electricity but for whom the production is not their principal activity.
  - 2) Ownership of renewable energy capacity in Germany. This indicates how much of the installed renewable energy capacity in Germany is in citizens hands. Even if potential for renewables is context specific, it provides indicators for the potential beyond Germany.

The model input parameters are summarised in **Table 16**.

**Table 16:** Model input parameters for the development of onshore wind and grid development projects

Model input parameter	Unit of the data	Available geographies	Data source(s)	Availability
<b>Citizen ownership developments</b>	Electricity production capacity in MW by autoproducers <sup>23</sup> for wind, PV, solar thermal, wave/tidal/ocean energy  Percentage of capacity by	EU 28	<a href="#">Eurostat, 2021</a>	Open

<sup>23</sup> enterprises which produce electricity but for whom the production is not their principal activity

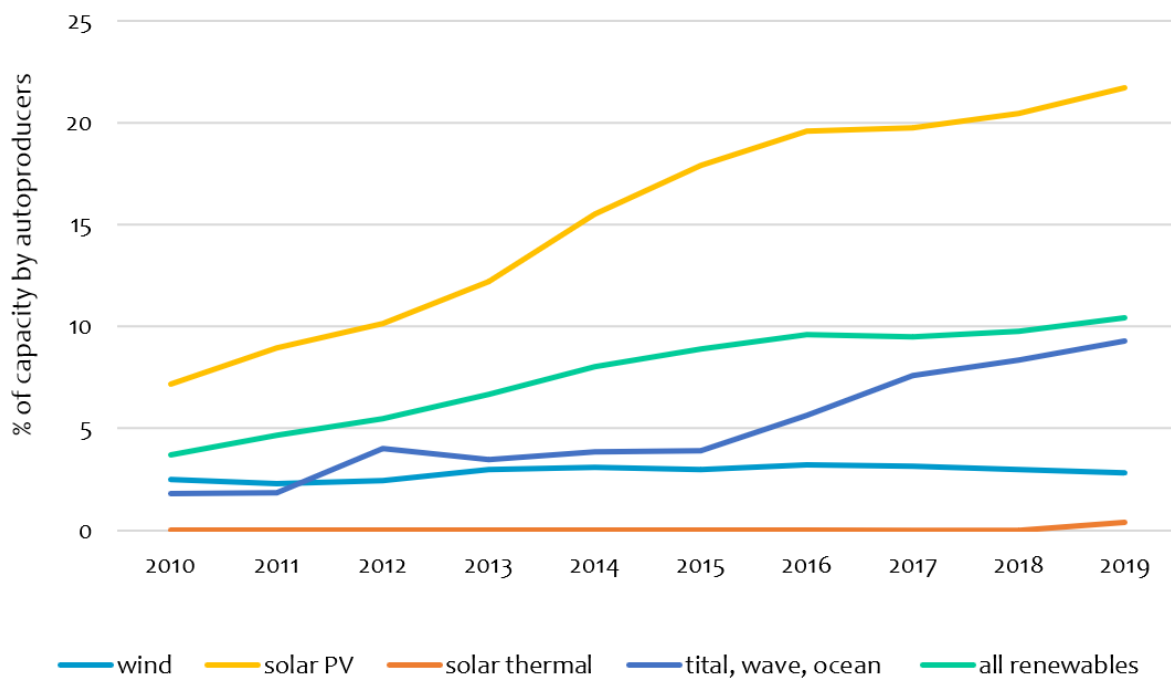
	autoproducers for wind, PV, solar thermal, wave/tidal/ocean energy [%]			
--	--	--	--	--

(continued table)

Note that the data for autoproduction provide only an approximation for citizen energy. Further information on the data availability, limitations, and analysis can be found in **Appendix 5**.

#### 4.2.5.3 Findings of the analysis

In 2019, 10.4% of electricity capacity in the EU 28 was owned by citizens (private individuals and non-energy businesses), as illustrated in **Figure 21**. The share of autoproducers for solar PV capacity was even 22%. This was equivalent to a capacity of 34 GW for different renewables, and 28 GW for solar PV (cf. **Figure A 13, Appendix 5**).



**Figure 21:** Development of autoproducers in the EU 28. Data source: Eurostat, 2021.

Comparison to other sources for which no data sets were (openly) available:

- The IEA<sup>24</sup> expects residential solar PV capacity to grow by 13 GW between 2019-2024 in its “main case” scenario (same as our calculations), and by as much as 18 GW in the same period in its “accelerated case”.
- According to a study by REScoop.eu & Friends of the Earth Europe (2016), there were 12 million private owners, or energy citizens, in the EU in 2015. Or 4.7% of electricity was generated by citizens in the EU. A report by CE Delft found that 264 million, or 45% of households could produce renewable electricity by 2050 (Kampman et al., 2016).

<sup>24</sup> <https://www.iea.org/reports/renewables-2019/distributed-solar-pv>

- In Germany, 40.4% of its citizens (individuals and farmers) own the installed renewable energy capacity<sup>25</sup> (AEE, 2017).

Note: A part of the citizen energy are collectives with different forms of citizen energy companies. For example, in 2016, there were 1747 citizen energy companies in Germany. Looking at the status since 1995, 94.22% of them still exist (as of 2016) (Kahla et al., 2017). Of the German citizen energy companies, around 883 are energy cooperatives with a total of around 200,000 members and an average of 215 members per cooperative (DGRV, 2020). In comparison, there are a total of 623 energy cooperatives in the Netherlands with a total estimated number of members and/or project participants of approximately 97,000 citizens (HIER climate foundation and RVO, 2020).

## 4.2.6 Private energy demand & service

### 4.2.6.1 Relevance and purpose of the quantification for modelling

Private energy demand depends on various factors. One essential aspect is the energy refurbishment status of buildings. The Energy Performance of Buildings Directive 2010/31/EU (EPBD) and the Directive amending the Energy Performance of Buildings Directive (2018/844/EU) set important targets:

- Article 9: "achieve a highly energy efficient and decarbonised building stock and ensure that long-term renovation strategies deliver the necessary progress in transforming existing buildings into ultra-low energy buildings, in particular through an increase in deep renovations".
- Article 10: "Renovation would be required at an average rate of 3% per year".

Depending on the future development of energy renovation, different energy demand profiles must be assumed in the models. Therefore, we have analysed past building renovation states to make empirically based assumptions for future developments. In addition, we considered the size of the dwelling, which also influences how much space per person needs to be heated.

### Research questions related to data

*How do different developments of energy efficient renovations influence the private energy demand?  
How does the housing size influence the future heating demand?*

### 4.2.6.2 Output data from QTDIAN

- **Available geographies:** EU 28
- **Format:** text files (CSV data format)
- **We provide six types of data:**
  - 1) The percentage of the building stock that is renovated each year. This indicates how many building renovations and what level of energy efficient renovation has taken place to make assumptions for future annual renovation rates. This also indicates how much energy efficiency improvements are expected from the building sector.
  - 2) Annual data for sizes of housing (houses and flats) in rooms per person. This shows the expected increase/decrease in the area that needs to be heated or cooled, which correlates with the demand for heating or electricity. It also allows to make assumption for possible future sizes of housing.

---

<sup>25</sup> <https://www.unendlich-viel-energie.de/studie-buergerenergie-bleibt-zentrale-saeule-der-energiewende>

- 3) The floor area of single- and multi-family houses. This indicates how many square meters of living area must be heated or cooled, and whether it is expected to be higher or lower living area, which has consequences on future energy demand.
- 4) Final energy consumption of appliances and lighting. This indicates whether the energy demand for lighting and appliances is increasing or decreasing, and whether energy efficiency policies have led to more efficient products.
- 5) Number of energy-consuming appliances. This indicates how many appliances households own. This also shows whether the numbers are increasing or declining and to what extent the number of appliances outplay energy efficiency improvements.
- 6) Share of electric vehicles in the EU. This indicates how much new electricity demand will develop from the transport sector.

The model input parameters are summarised in **Table 17**.

**Table 17:** Model input parameters on energy demand & services.

Model input parameter	Unit of the data	Data source(s)	Data availability
Energy building renovation rate ("total energy related" and different depths)	Average Percent [%] over five years (2012-2016)	Directorate-General for Energy (European Commission) et al., 2019	Open
Size of housing	Average number of rooms per person, annual Average number of rooms per person, annual	<a href="#">Eurostat</a> , 2019 <a href="#">Eurostat2</a> , 2020	Open
Floor area of single and multi-family dwellings	Total floor area of single-family dwellings [m <sup>2</sup> ], increase in % (2012-2016) Total floor area of multi-family dwellings [m <sup>2</sup> ], increase in % (2012-2016)	<a href="#">EU Buildings Observatory, EC, 2016</a>	Open
Private electricity consumption of appliances and lighting	Final energy consumption of appliances and lighting, ktoe; kWh; increase/decrease [%]	<a href="#">RC-IDEES - Integrated Database of the European Energy System (2000-2015), 2015</a>	Open
Energy-consuming appliances	Number of appliances	<a href="#">RC-IDEES - Integrated Database of the European Energy System (2000-2015), 2015</a>	Open
Electric mobility	Stock share [%]	Global EV Outlook (IEA, 2021b)	Open

Further information on data availability, limitations, and analysis can be found in the **Appendix 6**.

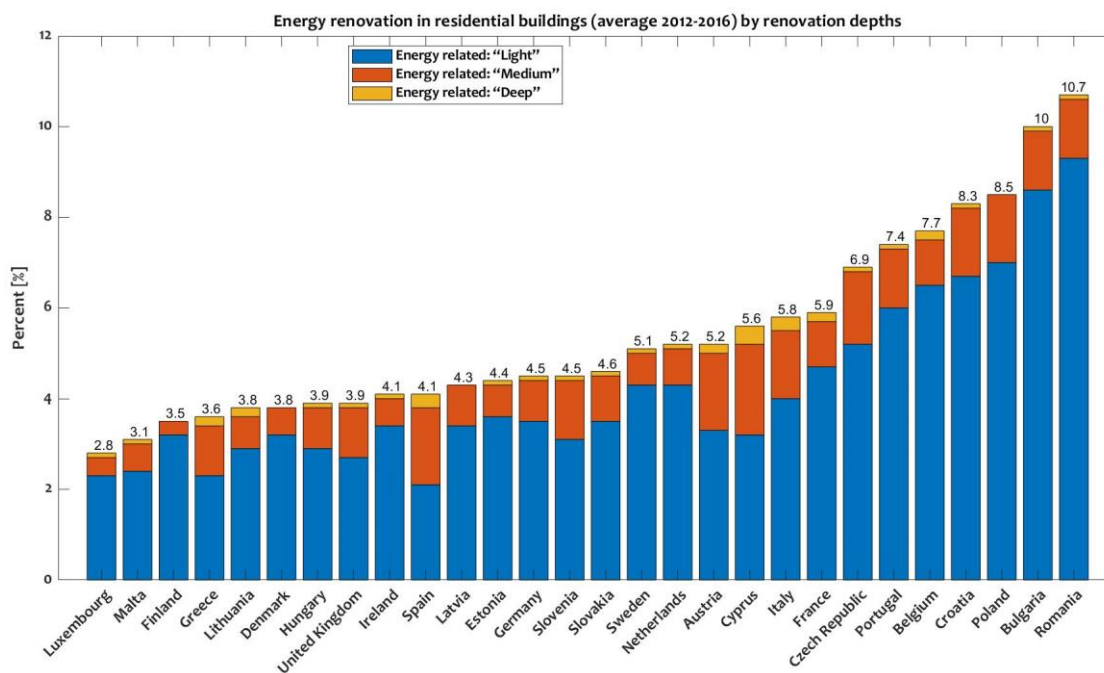
#### 4.2.6.3 Findings of the analysis

##### 4.2.6.3.1 Energy efficient building renovation

*In residential buildings:*

From 2012-2016, energy efficient building renovation in **the EU was 5%**, which corresponds to an **annual renovation rate of 1%/year**. Romania, Bulgaria, Poland, Croatia, and Belgium have the highest overall

energy renovation rates (sum of medium, light, and deep), amounting to 10.7%, 10.0%, 8.5%, 8.3%, and 7.7% respectively for the period of 2012-2016, as shown in **Figure 22**. Cyprus, Spain, and Italy have the highest deep energy building renovation rates of 0.4%, 0.3%, and 0.3% respectively for the period of 2012-2016.



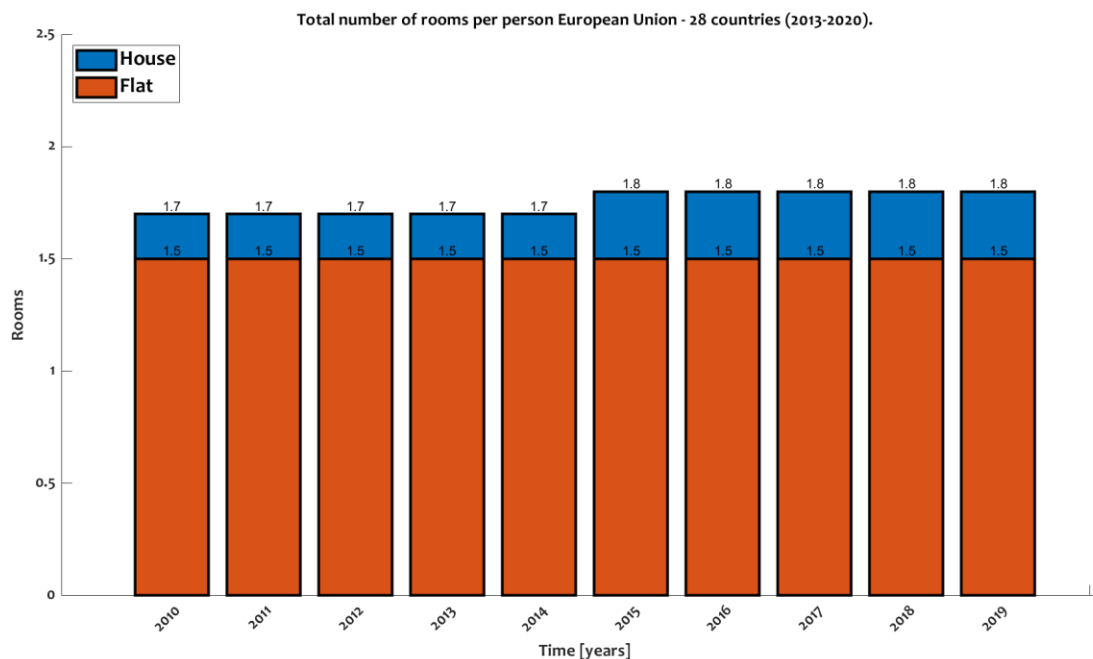
**Figure 22:** Energy renovation in residential buildings, sorted by overall renovation rate. Data source: Directorate-General for Energy (European Commission) et al., 2019.

#### *In non-residential buildings:*

From 2012-2016, the energy efficient building renovation in the EU was 5.4%, coming down to an annual renovation rate of 1.08%. Cyprus, Belgium, Portugal, Bulgaria, and Italy have the highest overall energy building renovation rates (sum of medium, light, and deep) with percentages of 14.5%, 12.3%, 11.2%, 10.7%, and 10.6%, respectively for the period of 2012-2016 (cf. **Figure A 14, Appendix 6**). Cyprus, Belgium, and Portugal have the highest deep energy building renovation rates with percentages of 1.0%, 1.0%, and 0.8% respectively over 2012-2016.

#### *4.2.6.3.2 Size of housing*

In 2019, on EU average, the size of flat was 1.5 rooms and the size of houses 1.8 rooms (**Figure 23**). The rooms in houses increased by 0.1 and the rooms in flats remained constant from 2010–2019. If we assume an average increase in the housing size of 0.1 as for the last ten years, the rooms in houses will be 1.9 rooms/person in 2030. If we assume a development in flat size following the current average, the rooms in flats will remain constant with 1.5 rooms/person.



**Figure 23:** Total number of rooms per person EU 28. Data sources: Eurostat, 2019, 2020.

#### *Rooms in houses: Country comparison*

In 2019, the highest number of rooms per person in a house were: 2.4 rooms/person in Malta, 2.2 rooms/person in Luxembourg, and 2.2 rooms/person in Ireland. In contrast, the smallest number of rooms in a house were: 0.9 room/person in Montenegro and 1.0 room/person in North Macedonia, Serbia, and Turkey, respectively. Lithuania, Sweden, and Hungary have the largest increase in the number of rooms per person in houses with 0.3, 0.2, and 0.1, respectively, in the last five years (2015–2019) (cf. **Figure A 15, Appendix 6**). Only Belgium experienced a decrease by 0.1 rooms.

#### *Rooms in flats: Country comparison*

In 2019, the highest number of rooms in a flat were: 2.1 rooms/person in Malta, 2.0 rooms/person in Cyprus, and 2.0 rooms/person in the Netherlands. In contrast, the smallest number of rooms in a flat in 2019 were: 0.8 room/person in Montenegro, 0.8 room/person in North Macedonia, and 0.9 room/person in Serbia. Hungary has the largest increase in the number of rooms per person in flats with 0.4 in the last five years (2015–2019). While Belgium, Montenegro, and Denmark have in the same period the largest decrease with 0.3, 0.2, and 0.1 respectively (cf. **Figure A 16, Appendix 6**).

#### *4.2.6.3.3 Floor area of single and multi-family dwellings*

##### *Total floor area of single-family dwellings*

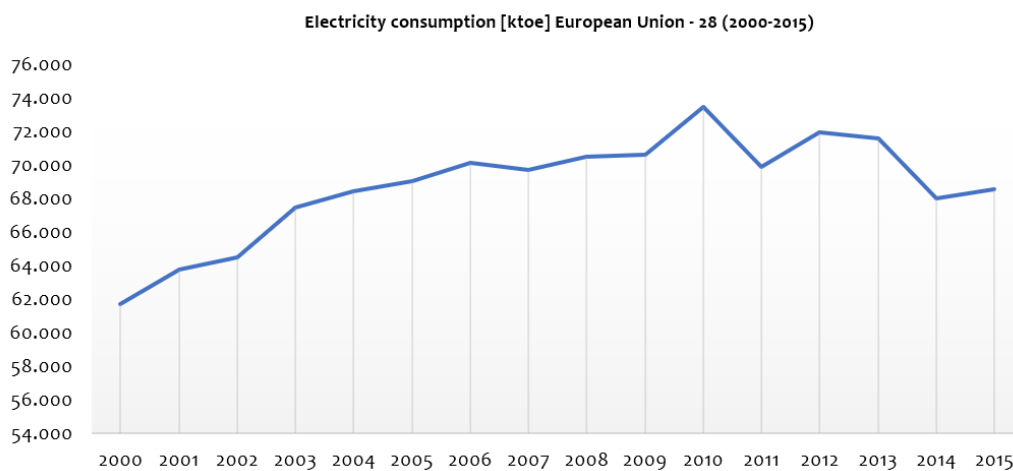
From 2012-2016, the total floor area of single-family dwellings has been increasing across the EU from 13.3 million to 13.5 million m<sup>2</sup>, with an average increase of 0.61% per year. The largest increase experienced Malta, where the floor area increased by 4.49%/year. In contrast, Italy experienced with 0.14%/year the lowest increase. There is no decline of floor area in any MS.

*Total floor area of multi-family dwellings*

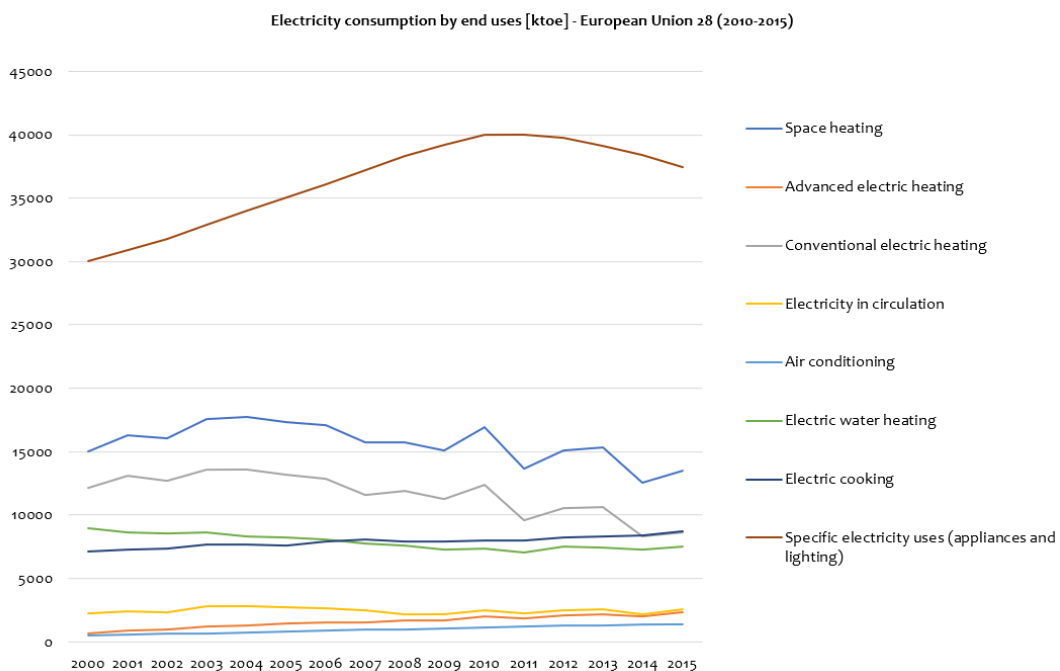
From 2012-2016, the total floor area of multi-family dwellings has been increasing across the EU from almost 7 million to close to 7.2 million m<sup>2</sup>, on an average of 0.68% per year. Luxembourg experienced the largest increase (floor area increased by 4.34%/year), whereas Greece saw the lowest increase (0.09%/year). There is no decline of floor area in any MS.

*4.2.6.3.4 Private electricity consumption*

The private electricity consumption in the EU has increased until 2010 to 73,465 ktoe and has fallen to 68,578 ktoe in 2015 (**Figure 24**).Figure 1



**Figure 24:** Electricity consumption in the European Union. Data source: JRC-IDEES - Integrated Database of the European Energy System (2000-2015), 2015.

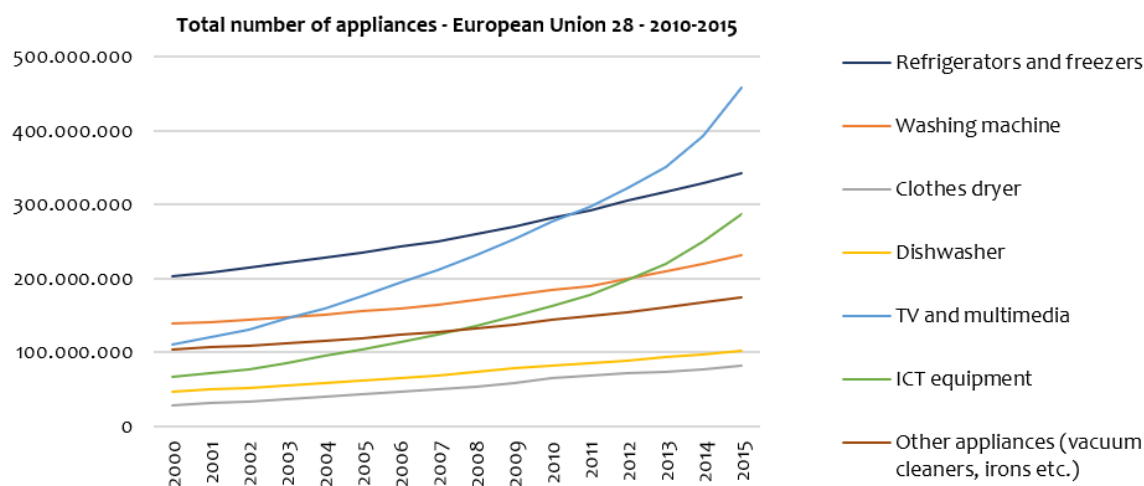


**Figure 25:** Electricity consumption by end uses. Data source: JRC-IDEES - Integrated Database of the European Energy System (2000-2015), 2015.

A closer look into the end uses shows that, from 2010-2015, electricity consumption for space heating (-3413.14 ktoe), conventional electric heating (-3780.60 ktoe) and appliances and lighting (-2555.90 ktoe) has been declining (**Figure 25** previous page). In contrast, electricity consumption increased for other end uses, such as electric cooking (+712.40 ktoe), advanced electric heating (296.85 ktoe) and air conditioning (+232.07 ktoe). Nevertheless, lighting and appliances make with 60% the largest share of the electricity consumed. Furthermore, space heating makes 21%, electric cooking 14%, electric water heating 12%, and air conditioning about 2%.

#### 4.2.6.3.5 Energy-consuming appliances and lighting

The numbers of electric appliances and lighting have been increasing across different types, from around 3.4 billion in 2000 to 5.2 billion in 2015 (**Figure 26**). From 2000-2015, the numbers of ICT equipment and TV and multimedia have quadrupled. In addition, clothes driers in the EU have tripled and dishwasher doubled, in the same timeframe. But what does this mean for the total electricity of appliances?

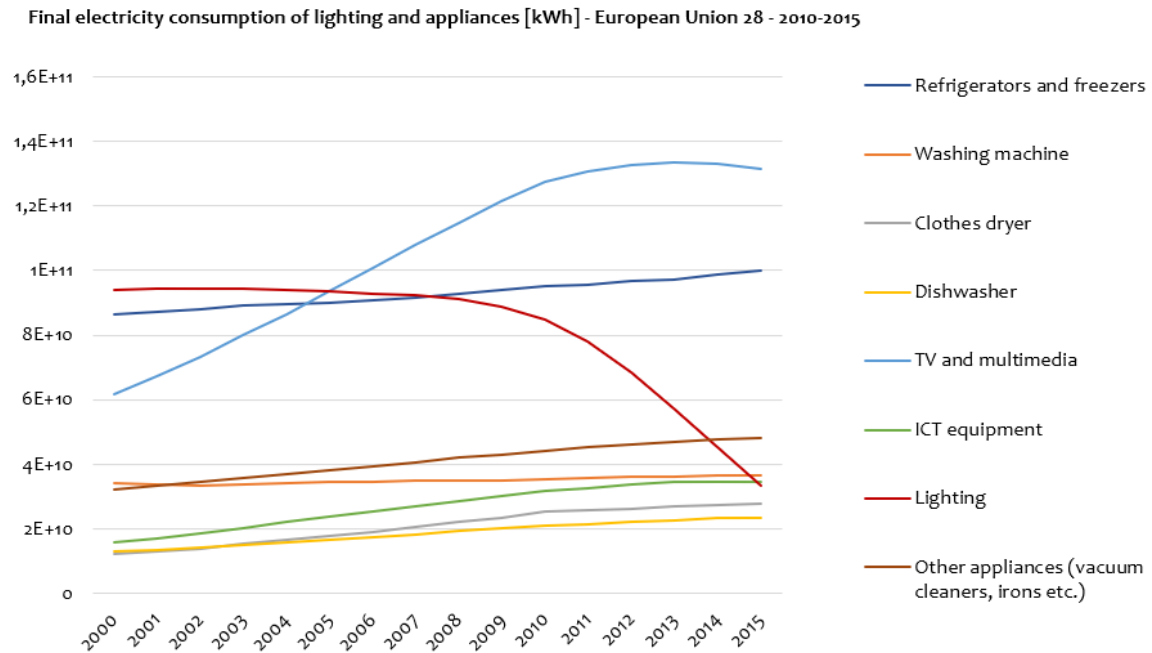


**Figure 26:** Total number of appliances in the EU. Data source: JRC-IDEES - Integrated Database of the European Energy System (2000-2015), 2015.

From 2010-2015, the electricity consumption per appliances has declined across different appliances and lighting. For example, TV and multimedia and ICT equipment require only half the electricity in 2015 compared to 2000. Refrigerators and washing machines have also become around 30% more energy efficient. This means that appliances and lighting have become more energy efficient.

However, the overall electricity consumption of electric appliances has only been declining for lighting and, lately, for TV and multimedia products (

**Figure 27**). Thus, this shows that although appliances and lighting have become more energy efficient and use less electricity per appliance, the increasing number of appliances overcompensates against energy efficiency improvements.



**Figure 27:** Final electricity consumption of lighting and appliances. Data source: JRC-IDEES - Integrated Database of the European Energy System (2000-2015), 2015.

#### 4.2.6.3.5 Electric mobility

The EU aims to reduce CO<sub>2</sub> emissions from cars by 55% (compared to 1990) by 2030 and proposes to ban sales of fossil-fuelled cars by 2035 (European Commission, 2019c). Electrification of transport plays an important role in reaching net-zero emissions by 2050 (IEA, 2021c). The International Energy Agency (IEA) Mobility Model projects 16 million electric cars in their *Stated policies scenario* in the EU by 2030 and 33 million in their *Sustainability development scenario* (IEA, 2021a). **Table 18** shows the IEA projections for the stock share of electric vehicles in the EU by 2030.

**Table 18:** Projections for the development of e-mobility in the EU by 2030. Data source: (IEA, 2021a)

Projection, Scenario 2030	Mode	% stock share
Sustainable Development Scenario	Buses	26.79
Sustainable Development Scenario	Cars	21.27
Sustainable Development Scenario	Trucks	9.98
Sustainable Development Scenario	Vans	33.38
Stated Policy Scenario	Buses	22.69
Stated Policy Scenario	Cars	12.37
Stated Policy Scenario	Trucks	1.7
Stated Policy Scenario	Vans	22.61

## 4.3 Linking storylines and quantifications

In the following, we link the different quantifications from **Section 4.2** to the three storylines (**Section 4.1**) and assign specific values to the different storyline characteristics in the respective storylines. We can only give assumptions for the future development of certain parameters based on current observations and trends. The storylines are designed to allow further quantification of parameters not quantified here and are open to further modification in future modelling efforts.

### 4.3.1 Socially feasible scaling and decline of energy technologies

The speed of technological diffusion does not depend on the storylines, because all storylines require that technologies will be developed quickly. However, how fast can it go?

Looking at **wind** power in Europe, the second fastest observed annual growth was in Denmark in 2013 with 657 MW or 6.13% of the total installed capacity (see section 4.2.1). Looking at **solar PV** in Europe, the fastest observed annual growth was in Italy with **8.0%** of total installed capacity in 2011. For combustible fuels in Europe, the fastest decline in combustible capacity was observed in Luxembourg with **20.4%** of total installed capacity in 2016. Outside Europe a high rate of expansion is observed mainly in China: The fastest observed annual growth rate for wind was 1.5% of installed capacity, 2.8% for solar and a 3.3% decline for combustible.

Based on empirically observed feasibility of scaling and decline of energy technologies, **we propose to assume a minimum upper limit for solar energy growth of 8%, for wind energy growth of 6.5% and for combustible fuels of 20 % (decline) of total installed capacity. This is independent of the social storylines, as it relates to the performance capacity of the supply chains and the opportunities to substitute generation technologies within the system.**

### 4.3.2 Policy preferences & dynamics

#### 4.3.2.1 Policy strategies

By analysing different policy and civil society documents, we were able to identify a majority and a minority pathway for the SENTINEL case studies. Based on the different political strategies, we extracted modelling assumptions for two of the three storylines in the three SENTINEL case studies (**Tables 19-21**).

#### European case study

**Table 19:** Storyline variables and suggested quantifications for two policy pathways for the EU

Storyline variables & values	People-powered	Market-driven
<b>Total GHG reduction targets</b>	65% reduction (GHG-1990) by 2030, net-zero by 2040 (cf. Table 7)	>55% reduction (GHG-1990) by 2030, 100%/ climate neutrality by 2050 (cf. Table 6)
<b>Renewable energy in gross final energy consumption</b>	>50% by 2030, 100% by 2040 (cf. Table 7)	32% by 2030, > by 2050 (cf. Table 6)

<b>Energy intensity</b>	25% energy intensity decrease (compared to projection for 2030) by 2030	32.5% energy intensity decrease (compared to projection for 2030) by 2030, > by 2050 (cf. Table 6)
<b>Fossil fuel phase-out</b>	Coal by 2030 Fossil gas by 2035 Fossil oil by 2040 (cf. Table 7)	No fixed dates
<b>Cross-border interconnection NTC</b>	≥5% of yearly power production by 2030	≥15% of yearly power production by 2030 (cf. Table 6)
<b>Residential building renovation</b>	1% per year	3% per year (cf. Table 6)
<b>Electric mobility</b>	>20% reduction in car use (cf. Table 7) No sale of new fuel-based cars by 2035 <sup>26</sup>	0% reduction in car use No sale of new fuel-based cars by 2035 <sup>27</sup>

(continued table)

**Explanation.** The assumed quantifications are largely based on current EU targets (cf. **Table 6, Market-driven**) and the PAC scenario (cf. **Table 7, People-powered**). The *people-powered* storyline follows the assumption that the citizens demand ambitious climate action in line with the 1.5° limit. Thus, targets for GHG reduction and renewable energy in the *people-powered* storylines are higher than in the Market-based storyline. However, compared to the PAC scenario, we assume that the renovation and energy intensity reduction are higher in the Market-based than in the *people-powered* scenario, as we aimed for higher differences between the two stories. Furthermore, the *people-powered* storyline sets a clear end date for the fossil fuel phase-out, while the market-based does not, as the market will decide when fossils become unprofitable. Cross-border interaction plays a much larger role in the Market-based storylines, as it assumes a European expansion logic for renewables, as it assumes a European expansion logic for renewables to minimise costs for all, without looking at other criteria, while in the *people-powered* storyline, production and consumptions is more local and follow a bottom-up logic. Energy demand decreases in both storylines along the targets of current EU policy (*market-driven*) and the PAC-scenario (*people-powered*). In general, we assume that the Market-based storyline will lead to higher residential renovation rates than the *people-powered* one, as citizens focus on renewable energy use instead of investing in renovation. Car use will be largely reduced only in the *people-powered* scenario, as citizens switch to other and shared modes of transportation. The Market-based storyline will trigger investments in electric cars, assuming a relatively stable overall use of cars.

### Nordic case study

**Table 20:** Storyline variables and suggested quantifications for two policy pathways for the Nordic countries

Storyline variables & values	People-powered	Governments-directed
<b>Total GHG reduction targets</b>	Carbon neutrality by 2035 (cf. Table 9)	-70% (GHG-1990) by 2030 (cf. Table 8) Net-zero emissions by 2045

<sup>26</sup> [https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal\\_en](https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en)

<sup>27</sup> [https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal\\_en](https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en)

<b>Renewable energy in gross final electricity consumption</b>	100% by 2040 (cf. Table 10)	55% by 2030; 100% by 2050 (cf. Table 8)
<b>Fossil fuel phase-out</b>	Coal by 2029 (cf. Table 9)	Coal by 2030 (cf. Table 8)
<b>Energy intensity</b>	-25% energy intensity decrease (compared to 2005) by 2030	-50% (compared to 2005) by 2030 (cf. Table 10)
<b>Residential building renovation</b>	1% per year (current trend, cf. section 4.2.6)	3% per year (cf. Table 9)
<b>Electric mobility</b>	Stop of sales for diesel and petrol cars by 2030 (cf. Table 8) >20% reduction in car use (cf. Table 7)	Stop of sales for diesel and petrol cars by 2030 0% reduction in car use

(continued table)

**Explanation.** For the Nordic case study, we assume policy targets by individual Nordic countries for the whole region (see references to country targets). In the *people-powered* storyline we propose to use Finland's targets for carbon neutrality and coal phase-out, implying a 10-year earlier carbon neutrality than in the *government-directed*. To achieve this, the electricity system will rely on 100% renewable energy by 2040, as Sweden is aiming for. Furthermore, we set more ambitious targets for energy intensity improvement and energy-efficient building refurbishment in the *government-directed*, given the governments Energy Efficiency First philosophy. In the *people-powered* storyline, the last diesel and petrol cars will be sold in 2030 (Danish target), and general car use will reduce (PAC scenario).

#### Greek case study

**Table 21:** Storyline variables and suggested quantifications for two policy pathways for Greece

Storyline variables & values	People-powered	Government-directed
<b>Total GHG reduction targets</b>	Climate neutral by 2050	-43% relative to 1990 by 2030 74.7% relative to 1990 by 2050 (cf. Table 12)
<b>Renewable energy in gross final energy consumption</b>	100% by 2050	35% by 2030; 67.6% by 2050 (cf. Table 12)
<b>Share in renewable energy and gas</b>	2050: Wind: 38.6% (37.15 onshore wind, 1.5% offshore wind); PV: 42.4%; Hydro: 14.8%; Bioenergy: 2.7; Geothermal: 1.6%; Gas: 0% (cf. Table 22 and Minority pathway)	2030: Wind: 26.6%; PV: 29.3%; Hydro: 14.8%; Bioenergy: 1.1%; Gas: 26.2% 2050: Wind: 31.4% (30.2% onshore, 1.2% offshore); PV: 34.5%; Hydro: 12%; Bioenergy: 1.5%; Gas: 20% (cf. Table 22)
<b>Fossil fuel phase-out</b>	Coal by 2025 (cf. Table 12)	Coal by 2025 (cf. Table 12)
<b>Energy efficiency intensity</b>	-25% (compared to 2005) by 2030	>38% (compared to the forecast by 2030) and lower total demand than in 2017 (cf. Table 12)
<b>Energy storage: installed capacity</b>	≥15% of yearly power production by 2030 (cf. Table 6)	2.2 TWh by 2030, 8.2 TWh by 2050 (cf. Table 12)
<b>Residential building renovation</b>	0.72% per year (current trend, cf. section 4.2.6)	3% per year

**Explanation.** In the *people-powered* storyline, citizens demand for ambitious national climate and energy targets in line with the Paris Agreements and the European Green Deal. Hence, we assume that Greece will be climate neutral by mid-century, using 100% renewable energy. This contrasts with the lower target of 74.7% reduction in GHG and 67.6% renewable energy by 2050 in the *government-directed* storyline. While coal is phased-out by 2025 in both storylines, Greece remains dependent on fossil gas in the *government-directed* storylines. This is in contrast to the bottom-up logic. In the *people-powered* story, Greece builds no new fossil gas infrastructures and completely phase out gas by 2050.

The Greek NECP sets specific objectives for installed renewable energy capacity in 2030 and 2050 (**Table 12**). Based on the NECP targets, we have calculated an electricity mix for 2030 and 2050 as percentages of the installed capacity, assuming gas will be still part of the electricity. Following the *people-powered* pathway, we have also calculated an electricity mix that assumes fossil gas is phased out by 2050 (**Table 22**, cf. **Figure A 7, Appendix 2**).

**Table 22:** Share of installed electricity capacity in Greece, assumed based on NECP and Long-term strategy 2050 targets in GW

Unit   Renewable energy source	2030		2050		2050 without gas	
	GW installed	%	GW installed	%	GW installed	%
Wind	7.0	26.6	10.2	31.4	10.2	38.6
Wind onshore			9.8	30.2	9.8	37.1
Wind offshore			0.4	1.2	0.4	1.5
Solar PV	7.7	29.3	11.2	34.5	11.2	42.4
Solar thermal	0.1					
Hydro	3.9	14.9	3.9	12.0	3.9	14.8
Bioenergy (biomass & biogas)	0.3	1.1	0.5	1.5	0.5	2.7
Geothermal	0.1	0.4	0.2	0.6	0.4	1.5
Gas	6.9	26.2	6.5	20.0	0	0
Petroleum products	0.3	0.01	0	0	0	0
all renewables	19.1	72.6	26.0	80.0	26.4	100
all sources	26.3	100	32.5	100	32.5	100.0

The *people-powered* storylines assumes higher storage capacity, applying a storage capacity in line with the EU target. The renovation of residential building in the *government-directed* story is expected to follow the EU goal of 3% – which is more than double the current Greek target. In contrast, we assume to follow the trend in the *people-powered* one, which was 3.6% the period 2012-2016.

#### 4.3.2.2 Distances and densities for onshore wind

Furthermore, our three storylines imply different assumptions for restrictions on the distances between onshore wind and settlements, as well as a maximum density for onshore wind in municipalities (**Table 23**).

**Table 23:** Storyline variables and suggested quantifications for onshore wind distances and densities

Storyline variables & values	People-powered	Government-directed	Market-driven
Distances onshore wind and housing	Use 500 meters for large turbines; and 200 meters for small turbines (max 40 dB) (average minimum low in the EU, cf. Table 13)	700 meters for large turbines and 200 meters for small turbines (40 dB) (cf. JRC model recommendation section 4.2.2))	Use 1000 meters (highest observed in the EU, cf. Table 13)
Density onshore wind energy in municipalities	No restrictions	8% of municipal area (found in Greece; cf. Table 13)	4% of municipal area (found in Greece; cf. Table 13)

**Explanation.** In the *people-powered* storyline, citizens generally accept local renewable energy developments, also because they actively participate in projects and benefit from revenues. Hence, setback distances are low (500 meters), and no density restrictions apply. In the *market-driven* storyline, acceptance for onshore wind is weak, also because citizens are rarely involved in the projects that are built by corporations. Therefore, we assume the largest setback distance observed in the EU (1000 meters) for this storyline. The *government-directed* storyline represents the middle ground between the two other storylines. Here, we suggest following the JRC assumptions for distances (40 dB at nearest building, 700 meters for large installations). We also assume that only 8% of the municipal area are available for onshore wind, as is the case in Greece for onshore wind priority areas. Due to local resistance, only half of this is assumed in the Market-direct storyline – which is in line with the restrictions for tourism areas in Greece (cf. **Table 13**).

### 4.3.3 Citizens' attitudes towards renewable energy

We propose to base the future deployment of renewable energy sources in the model on empirical surveys of support for different renewable technologies. Assuming that support for different renewable energy technologies is the same across Europe as in Germany, we propose two different approaches:

- First exploit the full potential for rooftop solar PV, then exploit the potential for geothermal, then exploit equally the potential for ground-mounted solar and offshore wind, and finally exploit equally the potential for onshore wind and biomass plants.
- Assume an electricity mix or basket based on support – see **Table 24**.

**Table 24:** Storyline variables and suggested quantifications for citizens' attitudes towards renewables

Storyline variables & values	People-powered	Government-directed
Electricity mix based on support	Roof-top PV: 42% Ground-mounted PV: 8% Onshore wind turbines: 26% Offshore wind turbines: 6% Biomass plants: 10% Geothermal energy: 8%	Roof-top PV: 21% Ground-mounted PV: 17% Onshore wind turbines: 13% Offshore wind turbines: 17% Biomass plants: 13% Geothermal energy: 19% (cf. Table 25, Germany)

**Explanation.** The support in the *government-directed* storyline is based on the current empirical data on the support of the different technologies for Germany and the resulting electricity mix. We calculated the electricity mix based on the relative weight of individual support values (average of 2017-2019)

(Table 25). In this storyline, citizens support renewable energy, but local opposition is decreasing because of the decline of conditions for public participation and ownership.

**Table 25:** Agreement with the expansion of renewable technologies, 2017-2019, Germany, and calculation of trend and electricity mix based on Wolf (2020).

Renewable energy sources	Agreement in 2017	Agreement in 2018	Agreement in 2019	Average support values	Electricity mix based on support
Roof-top PV	80%	81%	85%	82%	21%
Ground-mounted PV	80%	59%	63%	67%	17%
Onshore wind turbines	44%	56%	51%	50%	13%
Offshore wind turbines	66%	64%	69%	66%	17%
Biomass plants	47%	46%	54%	49%	13%
Geothermal energy	73%	74%	78%	75%	19%
<b>Total</b>					100%

In the *people-powered* storyline, citizens are often the project developers (or at least owners) and hence, they largely prefer and support technologies where they individually or collectively benefit from owning technologies (cf. Bauwens and Devine-Wright, 2018; Süsser and Kannen, 2017). Consequently, we assume a doubling of shares for solar PV as well as onshore wind, compared to the *government-directed* storyline, making wind and solar the central pillars of the energy transition (Gerhards et al., 2021), and lower the shares for other sources.

In the Market-based storyline, industry does not care about public acceptance and builds infrastructure where it is cheapest. Since citizens cannot participate directly, they are more likely to prefer technologies that are not in their backyard and affect their local environment.

#### 4.3.4 Barriers to infrastructure developments

The storylines are characterised by barriers to infrastructural developments. **Table 26** summarises the key variables and quantifications in the context of the three storylines.

**Table 26:** Storyline variables and quantifications for barriers to infrastructure developments

Storyline variables & values	People-powered	Government-directed	Market-driven
Wind power realisation duration	14 months	10 months (lowest observed in Germany, cf. Figure A 10)	24 months (cf. Figure A 10)
Wind power projects with litigation process	10%	20% (cf. Table A 1)	30%
Grid development transmission	No new projects start, Projects currently (2021) under construction finished	300 projects, 45,000 km by 2040 (planned TYNDP2020 projects) (cf. Figure A 11)	400 projects by 2040

Delays grid transmission projects	No new projects start 50% of under construction are delayed, by on average 34 months	17% of the projects are delayed (status-quo among TYNDP projects), with average delay of 17 months (cf. section 4.2.4)	8.5% of the projects are delayed, with average delay of 8.5 months
Grid-scale storage projects	13 projects with 29,000 GWh storage capacity (planned TYNDP2020 projects)	26 projects with 29,000 GWh storage capacity (planned TYNDP2020 projects) (cf. section 4.2.4)	39 projects with 29,000 GWh storage capacity (planned TYNDP2020 projects)
Delays in grid-scale storage projects	No new, 40% of the projects are delayed	33% of the projects are delayed	40% of the projects are delayed

(continued table)

**Explanation.** In the *government-directed* storyline, the developments are largely aligned with the current situation as described in section 4.2.4. In this sense, it is a continuation of the present, seeing the implementation of current plans.

In the *people-powered* storyline, we assume that opposition against new wind projects is lowest, not holding delays and litigations completely, but rather reducing them, because citizens own it and benefit themselves directly or via the regional economy. The opposition against transmission, in contrast, is high, because the focus of the generation expansion is local, reducing the need and case for transmission. Hence, there are no new transmission projects, the already ongoing ones are subject to strong opposition: 50% of the projects are delayed, with the double the delay as of today.

In the *market-driven* storyline, companies develop projects with little citizen involvement, and thus people do not see the benefits locally, leading to resistance to wind where citizens live. Therefore, number of complaints increases, resulting in longer delays and more projects being affected by litigation. Because the *market-driven* storyline seeks to minimise costs, it is strongly focused on transmission, so that this storyline eventually sees a stronger expansion of the transmission grid than the *government-directed* storyline. People do not oppose transmission as such because they see that it reduces the cost, which is their primary aim.

#### 4.3.5 Citizen energy

For each of the three storylines, we assume different development for citizens active involvement in the energy transition. **Table 27** summarises the key variables and quantifications in the context of the three storylines.

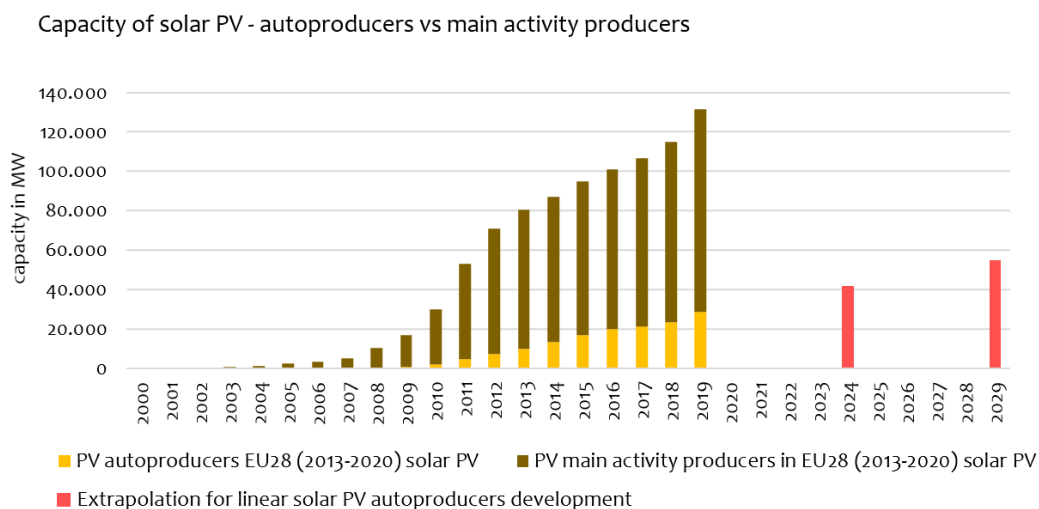
**Table 27:** Storyline variables and quantifications for citizen energy

Storyline variables & values	People-powered	Government-directed	Market-driven
Citizen ownership development	45% of electricity capacity by 2050 (almost status-quo in Germany today) (see section 4.2.5), >80% for solar PV (>100 GW) by 2050	34% of electricity capacity by 2050; >74% for solar PV (>100 GW) by 2050 (linear development of current trend) (cf. Figure 28)	11% of electricity capacity (34 GW) by 2050; 22% for solar PV (28 GW) by 2050 (status quo in Europe today) (cf. Figure 21)

**Explanation.** We assume the highest increase in citizen energy in the *people-powered* storyline. In this storyline, citizens actively participate in the energy transition.

In the *government-directed* storyline, we propose to assume a development based on the linear trend of autoproducers in the EU. Over the last 10 years (2010-2019), the share of autoproducer capacity increased by 0.76% per year on average. Assuming the same increase until 2050, autoproducers could hold ~34 % of installed electricity capacity. The share of autoproducer capacity for solar PV even increased by 1.7% annually. Assuming this increase until 2050, this would lead to a share of self-generating capacity of up to 74%. Over the last 10 years (2010-2019), the growth in self-generation capacity for solar PV was 26 GW, as shown in **Figure 28**. If we extrapolate this growth for the next 5 years and 10 years, solar PV could reach 42 GW of self-generation capacity by 2024 and 54 GW by 2029. Extrapolating a steady 10-year growth for 2050, we would expect that more than 100 GW of solar PV could be in the hands of self-generators.

In the *people-powered* storyline, we assume that the share of energy citizens could be even higher. In the past, Germany's renewables expansion has had strong decentralisation elements, and over 40% of the renewable power capacity is in the hands of citizens and farmers (AEE, 2017). The highest potential for the expansion of citizen energy is in rooftop PV. In contrast, there is no collectively owned offshore wind energy project, not least because they require much higher investments and are technically very complex. We propose to use the current German citizen-energy share as the central assumption for the *people-powered* storyline. The *market-driven* storyline does not provide opportunities for citizens to participate, so we assume a constant share of citizen energy (European current average).



**Figure 28:** Potential future development of PV autoproducers.

#### 4.3.6 Private energy demand & service

For each storyline, we assume different developments for building renovation and rooms per person. **Table 28** summarises the key variables and quantifications.

**Table 28:** Storyline variables and quantifications for private energy demand & services

Storyline variables & values	People-powered	Government-directed	Market-driven
Building renovation (residential, floor space)	Deep renovation rate of 0.2% annually; medium renovation of 1.1% (current trend <sup>28</sup> )	Deep renovation rate of 2.1% annually, 0.9% medium renovation (Renovation rate of 3% of which 70% are deep renovations (PAC scenario))	Deep renovation rate of 3% annually (BPEI report)
Rooms per person	<p><i>EU case study:</i> House: 1.7, Flat: 1.2 (assuming trend for Belgium for the whole<sup>29</sup>)</p> <p><i>Nordic case study:</i> House: 1.6, Flat: 1.5 (assuming IS and SE low, respectively, for all Nordic countries)</p> <p><i>Greek case study:</i> House: -0.1, Flat: 0.9 (assuming decrease trend of 0.1 of Belgium)</p>	<p><i>EU case study:</i> House: 1.8, Flat: 1.5 (status-quo of the EU, 2019<sup>30</sup>)</p> <p><i>Nordic case study:</i> House: DK: 2.1, IS: 1.5, NO:2.2, SE: 2.1 Flat: DK: 1.8, IS: 1.6, NO: 1.9, SE: 1.6 (assuming status quo)</p> <p><i>Greek case study:</i> House: 1.3, Flat: 1.3 (assuming status quo)</p>	<p><i>EU case study:</i> House: 2.1, Flat: 1.9 (assuming trend for Lithuania and Hungary, respectively, for the whole EU<sup>31</sup>)</p> <p><i>Nordic case study:</i> House: 2.2, Flat: 2.0 (assuming NO high for all Nordic countries)</p> <p><i>Greek case study:</i> House: 0.3, Flat: 1.7 (assuming increase trend of 0.3 of Lithuania and 0.4 of Hungary)</p>
Total floor area of single and multi-family dwellings	<p><i>EU case study:</i> Single: 13657344.8 m<sup>2</sup> (2016) (assuming status quo) Multi: 7163631.49 m<sup>2</sup> (2016) (assuming status quo)</p> <p><i>Greek case study:</i> Single: 160792.9 m<sup>2</sup> (2016) (assuming status quo) Multi: 212390.53 m<sup>2</sup> (2016) (assuming status quo)</p>	<p><i>EU case study:</i> Single: increase by 0.61% annually (current trend) Multi: increase by 0.68% annually (current trend)</p> <p><i>Greek case study:</i> Single: increase by 0.2% annually (current trend) Multi: increase by 0.09% annually (current trend)</p>	<p><i>EU case study:</i> Single: increase by 1.5% annually (current average trend of top 3 countries (except Malta)) Multi: increase by 2.3% annually (current average trend of top 3 countries (except Luxemburg))</p> <p><i>Greek case study:</i> Single: increase by 0.4% annually (double current trend) Multi: increase by 0.2% annually (double current trend)</p>
Private electricity consumption of appliances and lighting	Linear decrease as of today (EU)	Exponential decrease to meet 2030 target	Constant (market-driven increase of new appliances and use cases) <sup>32</sup>
Mobility: electric vehicles	No sale of new fuel-based cars by 2035 (Fit for 55 package); up to 22% of the private car fleet, 24% of vans,	No sale of new fuel-based cars by 2035 (Fit for 55 package); up to 13% of the private car fleet, 23% of vans,	Phase-out fuel-based cars by 2035 (Fit for 55 package) No new fuel-based cars by 2035 (Fit for 55 package); up

<sup>28</sup> <https://op.europa.eu/en/publication-detail/-/publication/97d6a4ca-5847-11ea-8b81-01aa75ed71a1/language-en/format-PDF/source-119528141>

<sup>29</sup> [http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc\\_lvho03&lang=en](http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc_lvho03&lang=en)

<sup>30</sup> [http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc\\_lvho03&lang=en](http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc_lvho03&lang=en)

<sup>31</sup> [http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc\\_lvho03&lang=en](http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc_lvho03&lang=en)

<sup>32</sup> "Energy efficiency of large electrical appliances continues to improve rapidly. However this effect does not counterbalance anymore the rapid growth of the consumption of small appliances."

<https://www.odyssee-mure.eu/publications/efficiency-by-sector/households/electricity-consumption-dwelling.html>

	27% of busses and 10% of trucks are electrified by 2030 (IEA Sustainable Development Scenario, IEA, 2021). By 2050 all remaining road transport will be electrified	23% of busses and 2% of trucks are electrified by 2030 (IEA Policy Scenario, IEA, 2021). By 2050 all remaining road transport will be electrified.	to 50% of the private car fleet is electrified (PAC scenario) and 60% of vans, 60% of busses and 40% of trucks are electrified. By 2050 all remaining road transport will be electrified.
Mobility: travelled distances	>20% reduction in car use by 2040 (compared to the baseline); Doubling of rail freight between 2015 and 2040, and a 12% shift in passenger km from car to bus, train, walk and bicycle combine (PAC scenario)	<20% reduction in car use by 2040 (PAC scenario); 25% increase of rail freight between 2015 and 2040, and a 6% shift in passenger km from car to bus, train, walk and bicycle combine	Transport modes remain the same as today; 0% reduction in car use

(continued table)

**Explanation.** In the *government-directed* storyline, we assume a deep **renovation rate** of 2.1% and a medium renovation rate of 0.9% per year, in line with the PAC scenario. In the *market-driven* storyline, we assume that all renovations are deep renovations. In both storylines we see targets of 3% in line with the overall EU target. In contrast, in the *people-powered* storyline, citizens are more likely to invest in renewables and are, therefore, less interested in carrying out building renovations. Thus, we assume the renovation rate remains as today. To make full climate neutrality more achievable despite the lower renovation rate, **the living space (rooms per person and total floor area)** in this storyline is lower than in the others, and we assume a decrease in living space – using the observed trend in Belgium of -0.3 rooms/person over five years for flats and -0.1 rooms/person in houses – for the whole EU.

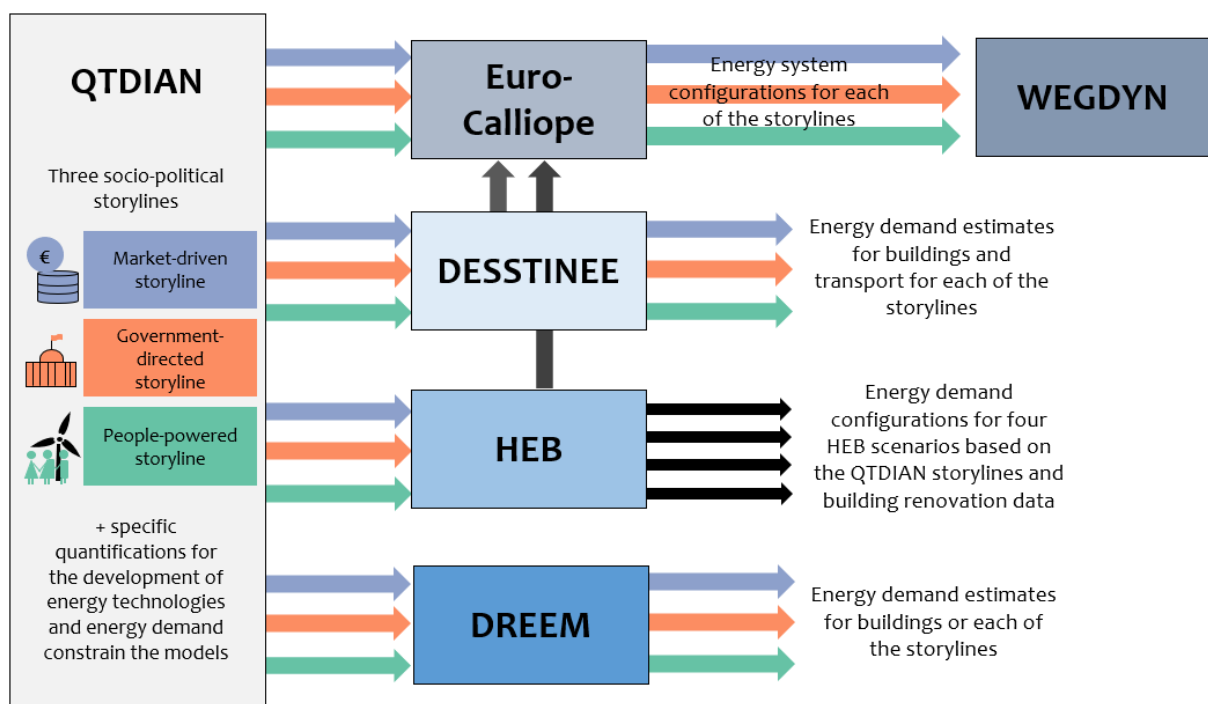
In the *market-driven* storyline, we assume that the markets will drive people's desire for a larger **living space** and that rooms per person will increase. We assume the largest increase of rooms per person – in Hungary with 0.4 rooms/person for flats, and in Lithuania with 0.3 rooms/person – will be in the whole EU. The market will also drive high annual investments in renovations, as a cost-effective means to reduce emissions and enable climate neutrality.

The **electricity consumption of lighting and appliances** will decrease as the current trend in the *people-powered* storylines. In contrast, in the *market-driven* storyline, we assume that number of appliances and use cases outweigh energy-efficiency savings in electricity consumption and remain at the current trend. In the Government-driven storyline we see an exponential decrease in line to meet the 2030 targets

In the **mobility sector**, car use will be largely reduced only in the *people-powered* scenario, as citizens switch to other and shared modes of transportation. The remaining car-fleet will be fully electrified by 2040. The *market-driven* storyline will trigger investments in electric cars, assuming a relatively stable overall use of cars. In line with the 'Fit for 55' package, there are no new fuel-based cars from 2035 onwards. There is little emphasis on public and communal solutions: Public transport is hardly expanded. In the *market-driven* storylines, transport systems change only moderately. Public transport is expanded, but the number of cars on the street decrease only slightly. However, fuel-based car engines will be faced out by 2030 – as done by some countries.

## 5 Model linking

The social storylines and quantification from QTDIAN have been transferred into energy demand and system design models. Here, we show several ways how QTDIAN has been soft-linked to the energy system design model Euro-Calliope and the energy demand models DESSTINEE, HEB and DREEM (**Figure 29**). We implemented this linking to integrated empirical based development of social and political aspects of the energy transition into the model, and thus, to be able to perform a more realistic analysis of energy system trajectories. In the following sections, we provide further details on the linking applications and arising challenges, reworked from D2.5 (Süsser et al., 2021c).



**Figure 29:** Model linkages between QTDIAN and Euro-Calliope, DESSTINEE, HEB and DREEM. Adapted from (Süsser et al., 2021c)

### 5.1 Linking QTDIAN, Euro-Calliope and WEGDYN

#### 5.1.1 Linking QTDIAN and Euro-Calliope

##### 5.1.1.1 Description of Euro-Calliope

Euro-Calliope is a model based on the Calliope energy modelling framework. Calliope is a framework to build energy system models, designed to analyse systems with arbitrarily high spatial and temporal resolution, with a scale-agnostic mathematical formulation permitting analyses ranging from single urban districts to countries and continents (Pfenninger and Pickering, 2018). Its key features include the ability to handle high spatial and temporal resolution and to easily run on high-performance computing systems. A range of peer-reviewed publications have been based on Calliope models, including to study uncertain demand in district energy systems (Pickering and Choudhary, 2021, 2019); the levelised cost of power-to-methane in Europe (Morgenthaler et al., 2020); the impact of replacing cooking

technologies in Italy (Lombardi et al., 2019); and the alternative configurations of the energy system in terms of diverse spatial and technical deployment of renewable energy in Italy (Lombardi et al., 2020; Pickering et al., 2022) and Europe, using the Euro-Calliope model (Tröndle, 2020; Tröndle et al., 2020). The Euro-Calliope model used in this study is based on version 0.6.8 of the Calliope framework. It models the deployment of components of the energy system at a sub-national level, in 98 regions across 35 countries in Europe, as a linear programming problem. Its objective function is to minimise total system costs. The model is set up at hourly resolution for a full year, and it deploys technologies overnight to fulfil hourly demand in each modelled region.

Like all energy system models, Euro-Calliope is built on a set of assumptions that are driven by the modelling team (Ellenbeck and Lilliestam, 2019). These often reflect the latest literature from a techno-economic perspective as well as a prevailing view from the energy modelling community on the viability of certain technologies (for instance, CSP has lost policy support in Europe, even if it is a technically viable technology (Lilliestam et al., 2021)). To better ground the main model assumptions, and to constrain otherwise free variables to reasonable ranges, we believe it is pertinent to incorporate rigorously researched social-political storylines from the very beginning. This ensures that the Euro-Calliope model and its results represent future energy pathways that are aligned with broader, observed social realities.

### 5.1.1.2 Method to link QTDIAN with Calliope

**Figure 29** shows how linking QTDIAN and Calliope would shape our understanding of future pathways. We settled on nine different parameters for policy targets and infrastructure developments, listed in **Table 29**. For each of the storylines, we assume different assumptions for the future developments and different renewable energy potentials ( ), based on the storyline logics. The values for the different variables are underpinned either by policy documents, or broader societal developments. Box 1 provides explanations for the parameter values. It is important to note that not all storyline elements and quantifications of QTDIAN have been used by Euro-Calliope, and some are used indirectly by using energy demand projections simulated by demand models which have included QTDIAN assumptions (more details are provided in (Süsser et al., 2021c)). Furthermore, we use different renewable energy potentials for each storyline, as shown in **Table 30**, on page 85. We use these parameters by following the data processing workflow described in (Tröndle et al., 2019).

**Table 29:** Input parameters included from QTDIAN in Euro-Calliope (for 2030 and 2050). Note: This is work in progress and reflects the status November 2022.

Storyline variables & values	People-powered	Government-directed	Market-driven
<b>Total GHG reduction targets</b>	>65% reduction (GHG-1990) by 2030 (PAC scenario; Climate Action Network Europe and European Environmental Bureau, 2020) 100% climate-neutrality by 2050 <sup>33</sup>	>55% reduction (GHG-1990) by 2030 ('Fit for 55' package, European Commission, 2021) 100% climate neutrality by 2050 (European Green Deal, European Commission, 2019) In 2030, non-energy sectors realise a max. 20% reduction,	>55% reduction (GHG-1990) by 2030 ('Fit for 55' package, European Commission, 2021) 100% climate neutrality by 2050 (European Green Deal, European Commission, 2019) In 2030, non-energy sectors realise a max. 20% reduction,

<sup>33</sup> The PAC scenario defines the target of net-zero by 2040. Euro-Calliope, however, does not consider an intermediate target for 2040.

	In 2030, non-energy sectors realise a max. 30% reduction, placing an additional decarbonisation burden on the energy sector.	placing an additional decarbonisation burden on the energy sector.	placing an additional decarbonisation burden on the energy sector.
<b>Renewable energy in gross final energy consumption</b>	>50% by 2030, (PAC scenario; Climate Action Network Europe and European Environmental Bureau, 2020) 100% by 2050 <sup>34</sup>	40% by 2030 ('Fit for 55' package, European Commission, 2021) > by 2050	40% by 2030 ('Fit for 55' package, European Commission, 2021) > by 2050
<b>Renewable energy mix</b>	Roof-top solar is explored to minimum 50% in 2030 and 80% in 2050 <sup>35</sup> . Limit of 20% available open field land area for use by PV, the rest is available for onshore wind. Limit of 10% of offshore area for wind.	Mix of rather centralised and decentralised energy technologies <sup>36</sup> .	The cheapest mix.
<b>Fossil fuel phase-out</b>	Coal by 2030 (PAC scenario; Climate Action Network Europe and European Environmental Bureau, 2020) <sup>37</sup> Fossil gas and oil by 2050.	Coal capacity in 2030 cannot be higher than the years before. Coal phase-out for all countries that have set targets to do so by 2030 ; coal power possible for countries with no or later phase-out targets Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czechia, Montenegro, Romania, Poland and Serbia (Europe Beyond Coal, 2021). Fossil gas and oil by 2050	No fixed dates. Coal capacity in 2030 cannot be higher than the years before.
<b>Nuclear phase-out</b>	Phase-out for some countries before 2030 <sup>38</sup> ; assume minimum installed capacities for remaining countries by 2030. All phase-out by 2050.	Phase-out for some countries before 2030 <sup>39</sup> , assume maximum installed capacities for remaining countries by 2030.	Phase-out for some countries before 2030 <sup>41</sup> . No minimum or maximum in 2050, but limited to countries which have nuclear today.

<sup>34</sup> The PAC scenario defines the target of 100% by 2040. Euro-Calliope, however, does not consider an intermediate target for 2040.

<sup>35</sup> The assumption for roof-top PV developments are based on current trends of the electricity production capacity in MW by autoproducers (enterprises which produce electricity but for whom the production is not their principal activity.), Source: (Eurostat, 2021); trend calculation (Süsser et al., 2022a)

<sup>36</sup> Equal electricity production by rather decentralised ("wind\_onshore\_competing", "wind\_onshore\_monopoly", "roof\_mounted\_pv", "chp\_biofuel\_extraction", "chp\_wte\_back\_pressure", "chp\_methane\_extraction") and centralised ("open\_field\_pv", "wind\_offshore", "ccgt", "hydro\_reservoir", "hydro\_run\_of\_river", "nuclear") technologies

<sup>37</sup> The PAC scenario defines the phase-out of fossil gas by 2035 and fossil oil by 2040. Euro-Calliope, however, does not consider an intermediate targets.

<sup>38</sup> Belgium by 2025 (<https://world-nuclear.org/information-library/country-profiles/countries-a-f/belgium.aspx>), Germany by 2022 ([https://www.base.bund.de/DE/themen/kt/ausstieg-atomkraft/ausstieg\\_node.html](https://www.base.bund.de/DE/themen/kt/ausstieg-atomkraft/ausstieg_node.html)), Spain by 2035, with sharp decline by 2030 (<https://world-nuclear.org/information-library/country-profiles/countries-o-s/spain.aspx>) and Switzerland plan nuclear phase-outs by 2034 (<https://world-nuclear.org/information-library/country-profiles/countries-o-s/switzerland.aspx>)

<sup>39</sup> Belgium by 2025 (<https://world-nuclear.org/information-library/country-profiles/countries-a-f/belgium.aspx>), Germany by 2030 (if possible), according to coalition agreement [https://www.spd.de/fileadmin/Dokumente/Koalitionsvertrag/Koalitionsvertrag\\_2021-2025.pdf](https://www.spd.de/fileadmin/Dokumente/Koalitionsvertrag/Koalitionsvertrag_2021-2025.pdf) , Spain by 2035, with sharp decline by 2030 (<https://world-nuclear.org/information-library/country-profiles/countries-o-s/spain.aspx>) and Switzerland plan nuclear phase-outs by 2034 (<https://world-nuclear.org/information-library/country-profiles/countries-o-s/switzerland.aspx>)

<sup>41</sup> Belgium by 2025 (<https://world-nuclear.org/information-library/country-profiles/countries-a-f/belgium.aspx>), Germany by 2030 (if possible), according to coalition agreement [https://www.spd.de/fileadmin/Dokumente/Koalitionsvertrag/Koalitionsvertrag\\_2021-2025.pdf](https://www.spd.de/fileadmin/Dokumente/Koalitionsvertrag/Koalitionsvertrag_2021-2025.pdf) , Spain by 2035, with sharp decline by 2030 (<https://world-nuclear.org/information-library/country-profiles/countries-o-s/spain.aspx>) and Switzerland plan nuclear phase-outs by 2034 (<https://world-nuclear.org/information-library/country-profiles/countries-o-s/switzerland.aspx>)

		By 2050 only allowed for countries which have stated possible future nuclear <sup>40</sup> .	
<b>Cross-border electricity interconnection</b>	<5% in each hour (send and received from another country) by 2030.	<15% of hourly exchange by 2030.	≥15% of hourly exchange by 2030 (Energy Community Secretary, 2021).
<b>Cross-border fuel exchange: synthetic fuels and hydrogen</b>	Mainly national autarky, reduced to 5%	Limited by 15% of trade (possible to change)	Free trade
<b>Grid development transmission</b>	Projects currently (2021) far in planning / under construction will be built by 2030 (TYNDP2020; ENTSO-E, 2021a, 2021b); No new projects between 2030 and 2050	Projects currently (2021) far in planning / under construction will be built by 2030. By 2050, additional projects which have been proposed, irrespective of current planning status, will also be added (TYNDP2020; ENTSO-E, 2021a, 2021b)	Projects currently (2021) far in planning / under construction will be built by 2030 (TYNDP2020; ENTSO-E, 2021a, 2021b). Further developments by 2050 are possible.
<b>Grid-scale storage (batteries) projects</b>	< 13 projects with 14,500 GWh storage capacity (TYNDP2020; ENTSO-E, 2021a, 2021b)	< 26 projects with 29,000 GWh storage capacity (TYNDP2020; ENTSO-E, 2021a, 2021b)	< 39 projects with 45,500 GWh storage capacity (TYNDP2020; ENTSO-E, 2021a, 2021b)
<b>Mobility: electric vehicles</b>	No sale of new fuel-based cars by 2035 <sup>42</sup> ; up to 22% of the private car fleet, 24% of vans, 27% of busses and 10% of trucks are electrified by 2030 (IEA Sustainable Development Scenario, IEA, 2021). By 2050 all remaining road transport will be electrified	No sale of new fuel-based cars by 2035 <sup>43</sup> ; up to 13% of the private car fleet, 23% of vans, 23% of busses and 2% of trucks are electrified by 2030 (IEA Policy Scenario, IEA, 2021). By 2050 all remaining road transport will be electrified	No new fuel-based cars by 2035 <sup>44</sup> ; by 2030, up to 50% of the private car fleet is electrified (PAC scenario; Climate Action Network Europe and European Environmental Bureau, 2020) and 60% of vans, 60% of busses and 40% of trucks are electrified. By 2050 all remaining road transport will be electrified
<b>Mobility: aviation</b>	Decline in aircraft fleet; overall reduction in energy demand by around 15.6% in 2030 and 36-4% in 2050 compared to 2015 (PAC scenario; Climate Action Network Europe and European Environmental Bureau, 2020) <sup>45</sup>	Stable aviation traffic with pre-covid 2019 energy demand	Intra-EU increase its share from 8% in 2015 to 12% in 2050, extra-EU: increase by 90% between 2015 and 2050; 14% of total energy demand by 2030, 17% of total energy demand by 2050 (EU Reference scenario, European Commission, 2021b)

(continued table)

<sup>40</sup> see D4.2, table 8, page 29 (Pickering, B., Roelfsema, M., Mikropoulos et al., 2022)

<sup>42</sup> [https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal\\_en](https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en)

<sup>43</sup> [https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal\\_en](https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en)

<sup>44</sup> [https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal\\_en](https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en)

<sup>45</sup> The numbers have been extrapolated; the PAC scenarios defines an overall reduction in energy demand by around 26% in 2040 compared to 2015

**Table 30:** Potentials defined in Euro-Calliope. See Tröndle et al. (2019).

Storyline variables & values	People-powered	Government-directed	Market-driven
<b>Renewable energy potentials</b>	'Technical-social potential' Use-of-protected areas: False PV-on-farmland: True Share-farmland-used: 0.2 (Agro PV) Share-forest-areas-used: 0.1 Share-other-land-used: 1.0 Share-offshore-used: 0.1 Share-rooftop-used: 1.0	'Technical-protected potential' Use-of-protected areas: False PV-on-farmland: True Share-farmland-used: 1.0 Share-forest-areas-used: 0.1 Share-other-land-used: 1.0 Share-offshore-used: 1.0 Share-rooftop-used: 1.0	'Technical potential' (no constrains) Use-of-protected areas: True PV-on-farmland: True Share-farmland-used: 1.0 Share-forest-areas-used: 1.0 Share-other-land-used: 1.0 Share-offshore-used: 1.0 Share-rooftop-used: 1.0

We have defined different parameter values based on the storyline-logics. The targets for greenhouse gas **reduction and for renewable energy in gross final energy consumption** in the *government-directed* and *market-driven* storylines are based on current EU target (European Commission, 2021, 2019). In contrast, the *people-powered* storyline follows the assumption that the people demand more ambitious climate action in line with the 1.5° limit. Thus, targets for 2030 in these storylines are higher than in the other two and are based on targets of the PAC scenarios (Climate Action Network Europe and European Environmental Bureau, 2020). The PAC scenario also defined targets for 2040, which is not a projection year considered by Euro-Calliope.

Following the different storylines logics, we assume different renewable energy mixes. In the *people-powered* storyline, citizens are often the project developers (or at least owners) and, hence, they largely **prefer** and **support technologies** where they individually or collectively benefit from owning them. Consequently, we assume large increases of shares for rooftop solar photovoltaics (PV) as well as onshore wind, making wind and solar the central pillars of the energy transition. For the *government-directed* storyline, we assume a balanced mix of more centralised and decentralised renewable energy sources, including municipal waste. In the *market-driven* storyline, industry does not care about public acceptance, but about getting projects done. Thus, they build technologies where they are cheapest.

Furthermore, the *people-powered* storyline sets a clear **end-date for fossil fuel**. The *government-directed* storyline also sets clear end dates for fossil fuel for those countries that have currently committed to phase-out coal. The *market-driven* storyline does not set any end date, as the market will decide when fossils become unprofitable. However, we assume that coal capacities will not be higher in 2030 than they are today. Regarding the **phase-out of nuclear energy**, we assume for each storyline that all countries which plan to phase-out by 2030, do so. For the other countries, capacities are set as of today. By 2050, there will be no nuclear energy in the *people-powered* storyline, in the *government-directed* storyline it is only available in countries that have stated future nuclear, and in *market-driven* there are no minimum and maximum capacities, but nuclear energy is limited to countries that use nuclear today.

**Cross-border interconnection** plays a much larger role in the *market-driven* storylines, as it assumes a European expansion logic for renewables, to minimise costs for all. In contrast, in the *people-powered* storyline, production and consumption are more local and follow a bottom-up logic.

When it comes to the **grid development**, we assume for all storylines that developments by 2030 are aligned with the current expansion plans under the ENTSOE Ten-Year Network Development Plan (TYNDP) 2018 (considering under construction/permitted planning/under consideration). Between 2030-2050, we assume no further grid expansion in the *people-powered* storyline. This is because there is opposition to transmission lines and, as the focus of the generation expansion is local, there is a reduced need and case for transmission. In contrast, the *market-driven* storyline seeks to minimise costs, which leads to very large potential expansion of cross-border transmission. In the *government-directed* storyline, all potential long-term transmission projects (according to the ENTSOE TYNDP) are considered to be constructed between 2030 and 2050, but no further expansion of the network is allowed.

**Synthetic fuels** are traded on a continental market and, on the one hand, no limitations are set on cross-border imports and exports in the *market-driven* storyline. On the other hand, the synthetic fuel market is limited respectively to 5% and 15% of the free-trade optimal solution when considering the *people-powered* and the *government-directed* storylines, respectively. No transportation cost is applied to the synthetic fuel's trades.

By 2035, there will be no new sales of **fossil-fuel engine vehicles** in all storylines, based on the current EU target, assuming that all remaining road transport will be electrified by 2050. By 2030, the share of electric cars on the roads is based on the IEA Global EV Outlook (IEA, 2022). We use the Sustainable Development Scenario (SDS), with a higher stock share of electric vehicles, in both *market-driven* and *people-powered* storylines. In the *government-directed* storyline, we use the Stated Policies Scenario (STEPS). In addition, the overall number of cars on the road differs between the storylines, with the expected change in number of vehicles coming from simulations undertaken in the DESSTINEE demand model. In the *people-powered* storyline, **car use** will be largely reduced as citizens switch to other and shared modes of transportation, such as public transport. The *market-driven* and *government-directed* storylines assume a relatively stable overall use of cars. **Aviation** will be mostly covered by liquid synthetic fuels and marginally by second-generation biofuels.

Ultimately, we limited the update of wind energy to the second fastest uptake observed in the EU: in Denmark in 2013 with 657 MW or 6.13% of the total installed capacity<sup>46</sup> (see **Section 4.2.1**). This is independent of the social storylines, as it relates to the performance capacity of the supply chains and the opportunities to substitute generation technologies within the system.

### 5.1.1.3 Linkage challenges

Not all elements of the storylines given in **Table 2** could be incorporated into Euro-Calliope – instead we focused on eleven variables. This is due to the difficulty in quantifying all aspects of storylines and the

---

<sup>46</sup> The fastest observed uptake for wind energy was in Montenegro in 2017, with 72 MW or 7.59% of the total installed capacity, but we excluded it because wind data for 2017 was 0 GW.

available locations in the Euro-Calliope dataset and model workflow in which quantifications can be included. For instance, the minimum distance of turbines from dwellings requires a high-resolution spatial dwelling database for the European continent, which is not available. The storyline elements included for incorporation in Euro-Calliope reflect what can be included with presently available data; in future model runs, should further data become available, additional QTIDIAN parameters can be included.

Conversely, Euro-Calliope offers many more areas for constraints to be added that cannot be provided by QTIDIAN at present. For instance, Euro-Calliope is represented at a high spatial resolution, but storyline outputs are limited to totals and averages across Europe as whole. Similarly, most constraints provided by QTIDIAN are annually aggregated and thus cannot capitalise on the sub-daily temporal resolution offered by Euro-Calliope. Finally, not all end-use energy sectors can be specifically constrained by the storylines. Space heat and hot water demand in buildings, fuel requirements in aviation, shipping, and industry processes can all be influenced by a change in systemwide 'energy intensity' (point 3. above) but not by targeted constraints.

Of those constraints that can be included, there is no particular challenge since the Calliope energy modelling framework is sufficiently generalised to enable the defined constraints to be applied without edits to the software itself.

## 5.1.2 Linking QTIDIAN, Euro-Calliope and WEGDYN

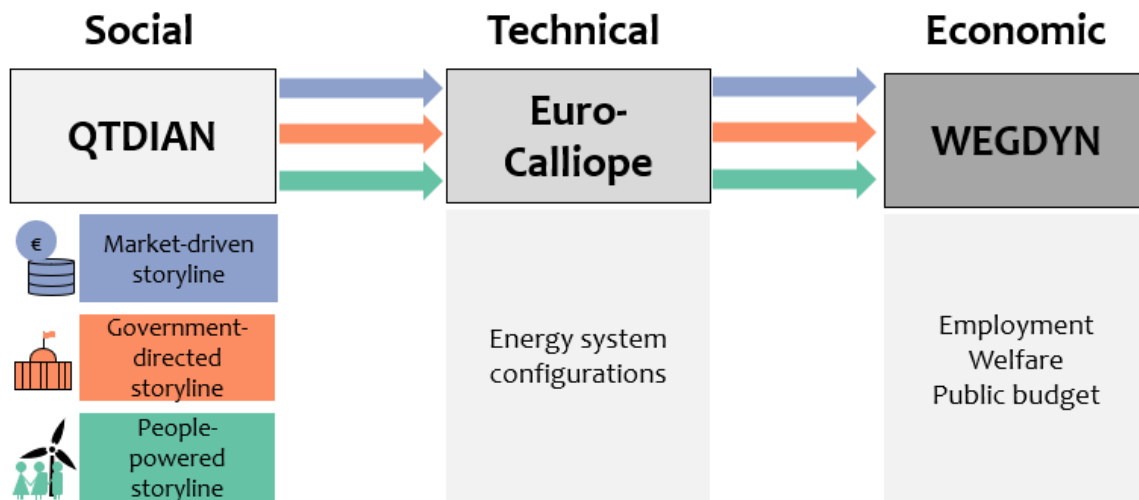
### 5.1.2.1 Description of WEGDYN

While the soft-link between QTIDIAN and Euro-Calliope is rich in technological terms, highly resolved temporally and spatially and augmented by crucial social and political factors, the scope and focus of this link lies on energy only. This makes the here presented sequential soft-link to the WEGDYN economic impacts model (Bachner et al., 2021) relevant in order to add relationships (and interactions) of energy (markets) with the production and consumption of goods and services other-than-energy. Hence, the global multi-region, multi-sector and multi-agent WEGDYN model adds otherwise unconsidered aspects and dimensions to the analysis of climate-neutral storylines, such as markets for labour, capital and emission allowances as well as an explicit representation of governments but also sectors and households outside Europe.

### 5.1.2.2 Methods to implement the QTIDIAN-Calliope-WEGDYN linkage

In section 5.1., we have described the linking between QTIDIAN and Calliope. The Calliope model has been further linked to the WEGDYN model (Bachner et al., 2022) in a sequential manner (**Figure 30**). We embedded the derived future energy system configurations, for each of the three storylines, in the WEGDYN model. This allows for an economy-wide assessment including indicators such as GDP,

welfare<sup>47</sup> and employment effects. A detailed quantitative explanation of this soft-link is reported in Michas et al. (2022).



**Figure 30:** QTDIAN-Calliope-WEGDYN model ensemble flow chart. Adapted from Michas et al. (2022).

### 5.1.2.3 Linking challenges

The direct quantitative soft-link between Euro-Calliope and WEGDYN is connected to issues about different model scopes and resolutions, convergence and uncertainty propagation. The strategies to deal with them are described in Michas et al. (2022). A further linking challenge between all three models has been identified and resolved by extensive discussions and collaborations between the modelling teams during the implementation of the linking process. One of the storylines (*people-powered*) assumes stronger bottom-up-driven emission reductions by 2030 than the other two, which is consistent with the logic of the concerning storyline but requires adjustments to warrant a “fair” and clean cost-effectiveness analysis using WEGDYN (i.e. comparing economic impacts for achieving the same emission reduction). This is done by fixing the supply of emission allowances in WEGDYN (corresponding to the EU case study specification of -55% GHG reduction by 2030 and 100% reduction by 2050) confronting it with the different demands for emission allowances across storylines, which are outputs from the Euro-Calliope model. This leads to different levels of emission allowances prices co-determining the economic impacts across storylines.

A direct link between QTDIAN and WEGDYN has been discussed and may prove interesting and relevant in future applications and concerns the handling of carbon pricing revenues. In the current default variant, WEGDYN assumes that revenues from carbon pricing increase public budgets, which is used for the consumption of public goods and services (e.g. health care, school system). Aligning this assumption with the logic of storylines would be possible and represent a direct link between the two models. The

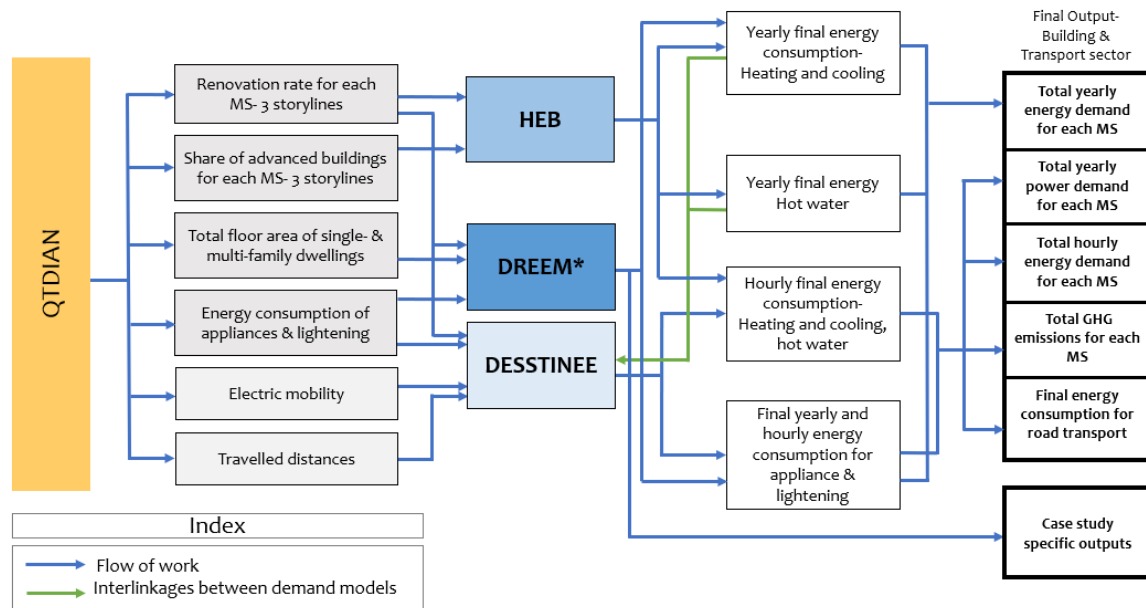
<sup>47</sup> Welfare is computed as Hicksian equivalent variation reflecting consumption possibilities of private and public households per region. In other words, it quantifies the willingness to pay for marketed goods and services at hypothetically unchanged relative prices that results in the same level of welfare.

default variant (i.e. increased public consumption) already matches with the logic of the *government-directed* storyline. By contrast, the *market-driven* storyline could be adjusted such to use the additional revenues from carbon pricing to reduce other taxes (e.g. taxes on labor or value added taxes) in a public-budget-neutral manner. The *people-powered* storyline could use higher tax revenues for paying equal-per-capita climate dividends to private households, for instance, to ameliorate potential regressive effects.

## 5.2 Linking QTDIAN and demand models

Long-term changes in the energy system are largely shaped by several socio-political factors, such as lifestyles and policies for energy-related appliances and renovations, and these factors impact both demand and supply (Cherp et al., 2018). Therefore, including socio-political factors into the SENTINEL demand models is essential to provide realistic future demand scenarios in the context of EU's commitment to climate neutrality. Therefore, in SENTINEL, the individual demand models are soft-linked with QTDIAN to include the socio-political aspects of the energy transition.

Soft-linking demand models with QTDIAN is a complex task as it requires the identification and quantification of different socio-political storylines that can be directly used as input by the demand models. Thus, after examining each of the demand models' input and output data requirements, along with their assumptions, we have identified six key parameters of the QTDIAN toolbox that can be used by the demand models. The magnitude of the six parameters namely, **(i)**. renovation rate, **(ii)**. share of advanced buildings within new and **(iii)**. renovated buildings, **(iv)**. energy consumption for appliances, **(v)**. electric vehicles, and **(vi)**. travelled distances, vary across the three storylines of QTDIAN to reflect different socio-political scenarios. Therefore, by using these parameters as input, demand models can produce more realistic future demand scenarios in the context of the climate neutrality target. Please see **Table 17: Model input parameters on energy demand & services.** for further details on the input data. **Figure 31** below summarises the soft-linking approach.



\*In case of the DREEM model, interlinkages will only be implemented for the case of the residential sector in Greece.

**Figure 31:** Linking QTDIAN as input for the three energy demand models; MS = Member States of the European Union. Adapted from (Süsser et al., 2021c)

## 5.2.1 Linking QTDIAN and DESSTINEE

### 5.2.1.1 Description of DESSTINEE

DESSTINEE is an open-source model developed at Imperial College London. It investigates the effects of demographic, economic, and technological changes on future final energy demand and power supply, both at yearly and hourly dimension. It has a country level geographical resolution, which can easily be expanded to cover sub-regions within a country. DESSTINEE has been used for simulating load curves under different decarbonisation scenarios, for example “two degree target scenarios” in the United Kingdom and Germany (Boßmann and Staffell, 2015).

DESSTINEE is programmed in VBA with a user-friendly interface in Excel. It is constituted by 3 modules. Module 1 forecasts annual final energy consumption, accounting for 11 energy carriers, using sectorial partial decomposition for service demand. The latter is projected based on user defined population and GDP growth rates, efficiency improvements, and fuel switching towards electric heat and transport. In the context of the SENTINEL project, this module has been employed with the purpose of defining technology incorporation and fuel baskets for final energy uses, compatible with climate neutrality by 2050 and newly announced decarbonisation targets by 2030 (Oreggioni G D, in preparation). For key final energy uses, annual figures for power usage are hourly distributed (Module 2), having the resulting power demand profiles been validated for all countries in Europe by crosschecking against official data for hourly system load.

Hourly power demand profiles can be used as input for the DESSTINEE’s Supply Module (Module 3) – allowing the simulation of the hourly operation of the power systems – by accounting for: user provided generation potential for intermittent renewable sources; assumptions for transboundary transmission

capacity; and efficiency and installed capacity figures for thermal generation plants. The model establishes a power matrix aimed at minimising running cost. Both for demand and supply, DESSTINEE reports fuel usage and fossil CO<sub>2</sub> emissions, and we are currently extending the model to also quantify other greenhouse gas emissions.

Forecasting service demand and final energy consumption relies on inputs and assumptions regarding behavioural changes, particularly, in terms of building occupancy, evolution for building surface area, thermal comfort patterns, and modal shifts for transport. Having access to detailed, and systemically obtained information in this domain will improve the accuracy and especially the policy relevance of the results as they will be closer connected to actual developments and pending political decisions. Linking DESSTINEE's inputs with QTDIAN outputs (and storylines) could significantly contribute to this.

#### 5.2.1.2 Method to link QTDIAN with DESSTINEE

As part of the interlinking work, outputs from QTDIAN are included in the simulation of the 2050 climate-neutrality scenario in DESSTINEE, employing the indicators presented in **Table 17**: Model input parameters on energy demand & services. Especially, we include:

1. Trends and projections for building renovation, for each QTDIAN storyline, will be used for estimating the improvement rates in building envelope efficiency. Currently, this value in DESSTINEE is nationally updated – considering building age profiles- and data from EU wide scenarios (European Commission, 2020b, 2018). Input from QTDIAN will be used for defining a future age profile for buildings, which will be supplemented with assumptions on building energy performance and country-level statistics for building stocks.
2. The future evolution for country-level household surface is currently forecasted, in DESSTINEE, as function of trends for national GDP per capita. Inputs from QTDIAN will be considered for defining an EU wide increase ratio whilst the afore mentioned mathematical relationships will be used for disaggregating total continental household area by countries.
3. DESSTINEE uses an appliance index to compute for the increase of power consumption within residential buildings. This index includes the effects associated with the trends in the number of appliances per building and the possible efficiency increases. This coefficient is, in DESSTINEE, currently based on projections for power usage for appliances – from EU wide scenarios- (European Commission, 2020b, 2018) and country-level functions that correlate power consumption with GDP per capita. The figures provided by QTDIAN, at continental level, will be considered to replace the data from the afore mentioned EU scenarios.
4. National increases for the service demand associated with passenger cars, in DESSTINEE, are based on the forecasts presented in the 2016's EU Reference Scenario (European Commission, 2016; Loulou and Labriet, 2008). These inputs will be replaced using the EU wide growth rate, informed by QTDIAN, whilst the data from the afore mentioned scenario will be accounted for allocating the total service demand among countries.
5. Future national fuel shares, within the passenger car fleet, are modelled in DESSTINEE based on: forecasts in continentally wide scenarios, econometric relationships for country-level electric

car ownership; and present distribution of biofueled units among Member States. Inputs from QTDIAN will replace the assumptions for electrification and fossil fuel shares, obtained from EU wide scenarios, whilst the national allocation methodology currently used in DESSTINEE will be kept.

### 5.2.1.3 Linkage challenges and possible benefits

For the variables considered in **Table 17** the integration between QTDIAN and DESSTINEE at continental level is quite straightforward. The main challenges are related to the downscaling of the EU defined targets into national circumstances. This could lead to estimates that could well define the whole EU27+UK bloc but that could be more uncertain at country level, both because national data is not always present and hence unknown, and because single policy decisions may have large effect on the national level, making the future more uncertain the deeper we zoom in. As indicated in 3.1.3, there are several final energy uses for which there are no constraints from QTDIAN such as the commercial sector or other passenger transport modes (rail, aviation and shipping). Since this is the first release of the model, this interlinkage exercise is a good starting point for future work – as further elaborated in the Discussion.

There are benefits of such an interlinkage, especially for the service demand quantification in heating in buildings and transport. In DESSTINEE, several aspects of service demand quantification account for the future evolution of income indicators. Updating such projections with figures that also consider possible behavioural changes is of great value – considering that some of these variables have a key societal component in terms of population and family dynamics, consumer preferences, and patterns for building refurbishing and mobility.

## 5.2.2 Linking QTDIAN and HEB

### 5.2.2.1 Description of HEB

The HEB (High Efficiency Buildings) model was originally developed in 2012 to calculate energy demand and CO<sub>2</sub> emissions of the residential and tertiary building sector by 2050 under three different scenarios (Petrichenko, 2014; Urge-Vorsatz, 2012). The HEB model calculates the energy demand in the four scenarios until 2060 based on the most recent data for macroeconomic indicators and technological development. This model is novel in its methodology as compared to earlier global energy analyses and reflects an emerging new paradigm: the performance-oriented approach to buildings energy analysis. The model takes a bottom-up approach, as it includes rather detailed technological information for the building sector, however, it also benefits from certain macroeconomic and sociodemographic data which include population, urbanisation rate, and floor area per capita. The four scenarios of HEB model are discussed below:

**Deep Efficiency Scenario:** The Deep Efficiency Scenario demonstrates the state-of-the-art of construction and retrofit technologies that can substantially reduce the energy consumption of the building sector and hence, CO<sub>2</sub> emissions, while also providing full thermal comfort in buildings. This scenario includes exemplary building practices that have been implemented in the EU for both new and renovated buildings.

**Moderate Efficiency Scenario:** This scenario incorporates present policy initiatives particularly the implementation of the Energy Building Performance Directive (EPBD) in the EU and building codes for new buildings in other regions. The key assumptions of the moderate efficiency scenario are presented in the **Table 31**.

**Frozen Efficiency Scenario:** This scenario assumes that the energy performance of new and retrofit buildings do not improve as compared to the baseline and retrofit buildings consume around 10% less than standard existing buildings for space heating and cooling. Furthermore, most new buildings have a lower level of energy performance than in moderate scenario due to lower compliance with building codes.

**Towards Net-Zero Scenario:** The last scenario models the potential of deploying “Net Zero Energy Buildings” – buildings that can produce as much energy locally through the utilisation of renewables as they consume on an annual balance. It differs from the other three scenarios to the extent that it not only calculates the energy consumption but already incorporates the local energy supply to arrive at the final energy demand. In other aspects, it uses the same parameters as the Deep Efficiency Scenario.

The aim of the scenario analysis is to capture the importance of different policy acts on building energy efficiency measures and show how much the final energy consumption of the building sector can be reduced across the EU. **Table 31** summarises the actual parameters of the four scenarios.

**Table 31:** Parameters of the four HEB scenarios. Source: Süsser et al., 2021c.

Parameter	Deep Efficiency Scenario	Moderate Efficiency Scenario	Frozen Efficiency Scenario	Towards Net Zero Scenario
<b>Initial renovation rate</b>	Country-specific data from the from IPSOS-Navigant report	Country-specific data from IPSOS-Navigant report	Country-specific data from the IPSOS-Navigant report	Country-specific data from the IPSOS-Navigant report
<b>Accelerated renovation rate</b>	Market-driven storyline renovation from QTDIAN after 2027	Government-directed storyline renovation data from QTDIAN after 2027	Country-specific data from the People-powered storylines from QTDIAN	Market-driven storyline from QTDIAN after 2027
<b>Energy Efficiency measures of new buildings</b>	New buildings are built to regional standards	New buildings are built to regional standards	New buildings do not improve as compared to the existing stock	New buildings are built to regional standards
<b>Energy efficiency measures of renovated buildings</b>	Renovations reduce the energy demand approximately by 30%	Renovations reduce the energy demand approximately by 30%	Renovations reduce the energy demand approximately by 10%	Renovations reduce the energy demand approximately by 30%
<b>Share of advanced buildings within New and retrofitted stock</b>	All new and retrofitted buildings have very low energy demand (advanced buildings) after 2027 in the EU	70% of the new and retrofitted buildings have very low energy demand (advanced buildings) after 2027	Advanced buildings are only introduced by the same share as present share of advance buildings	All new and retrofitted buildings have net zero energy demand after 2027 in the EU.

Based on these four scenarios, the key outputs of the HEB model are floor area projection for different types of the residential and tertiary buildings in different regions and Member States, the total energy

consumption of residential and tertiary buildings, energy consumption for heating and cooling, energy consumption for hot water energy, total CO<sub>2</sub> emission, CO<sub>2</sub> emission for heating and cooling, and CO<sub>2</sub> emission for hot water energy.

### 5.2.2.2 Method to link QTDIAN with HEB

Like most building demand model, the HEB model does not include socio-political indicators and hence, the scenarios of the HEB model may not be realistic enough to represent the future energy demand. Thus, by using QTDIAN storylines and the outcome of the storylines, HEB can include the socio-political aspect in each of the scenarios that make the scenarios much more realistic. Specifically, two of the key inputs used in HEB are building renovation rates, and share of advanced buildings for each of the EU MS. Both data vary across different scenarios and accordingly the final energy demand of the building sector is calculated for each of the scenarios.

1. **Renovation rate:** To better reflect the socio-political aspects in the HEB, we use the sum of medium and deep renovation rates for the initial renovation rate data from the IPSOS-Navigant report. The renovation data in QTDIAN varies as per storylines to reflect different socio-political scenarios, and by using the renovation data for each of the storylines, HEB scenarios include different socio-political storylines as well. For example, the renovation data for *people-powered* storyline is used as frozen efficiency renovation data in the HEB model. Similarly, the *government-directed* and *market-driven* storylines and data are used in the Moderate and Deep Efficiency Scenarios of the HEB model respectively. The renovation data reflects any type of retrofit that has a significant influence on the heating and cooling energy demand of the building.
2. **Share of advanced buildings within new and renovated buildings:** In the HEB model, scenario-specific assumptions are made on how much percentage of the renovated buildings are advanced (such as Net zero buildings, and passive houses) or non-advanced. These two categories reflect different energy efficiency levels where the non-advanced buildings are assumed to be the "business-as-usual", while advanced buildings are the technically possible best ones in terms of low energy consumption. Thus, for the Deep Efficiency and Towards net zero scenarios in the HEB model, we use the deep renovation data from the *market-driven* storyline of QTDIAN from assuming the share of advanced buildings. Similarly, for the moderate efficiency scenario, we use the data from *government-directed* storylines.

### 5.2.2.3 Linkage challenges and possible benefits

Any soft linking of the models faces certain challenges and linking QTDIAN and HEB is no exception either. The two major challenges while soft-linking these two models are the follows:

- In the QTDIAN input data from where the renovation rate is defined, the energy savings are expressed based on primary energy, while in HEB the specific energy use of buildings (consequently the savings too), as well as the output, is expressed in final energy. Thus, we have

assumed in HEB that there is no significant difference between savings in final energy and primary energy regarding building end-uses.

- In the HEB model, we aim to decouple building-related energy consumption from onsite production (e.g. photovoltaics), therefore the reduction in energy demand through PV installation is not considered within the savings between existing and retrofitted buildings. At the same time, the input data from the Ipsos-Navigant report used by QTDIAN consider this option when calculating the energy savings of the renovations. To account for this issue, we only use the share the renovation data for different storylines and use our assumption on energy savings or energy performance for advanced and non-advanced building types.

Apart from these challenges, there are some usual challenges as well, for instance, data comparability between two models, comparing the underlying assumptions of these two models etc. However, we could encounter these challenges to exhaust the benefits of soft-linking these two models. The biggest benefit of soft-linking QTDIAN and HEB is having more representative and realistic scenarios in HEB. Thus, the demand data produced by HEB are much more accurate and closer to the reality that can be better applied in policymaking.

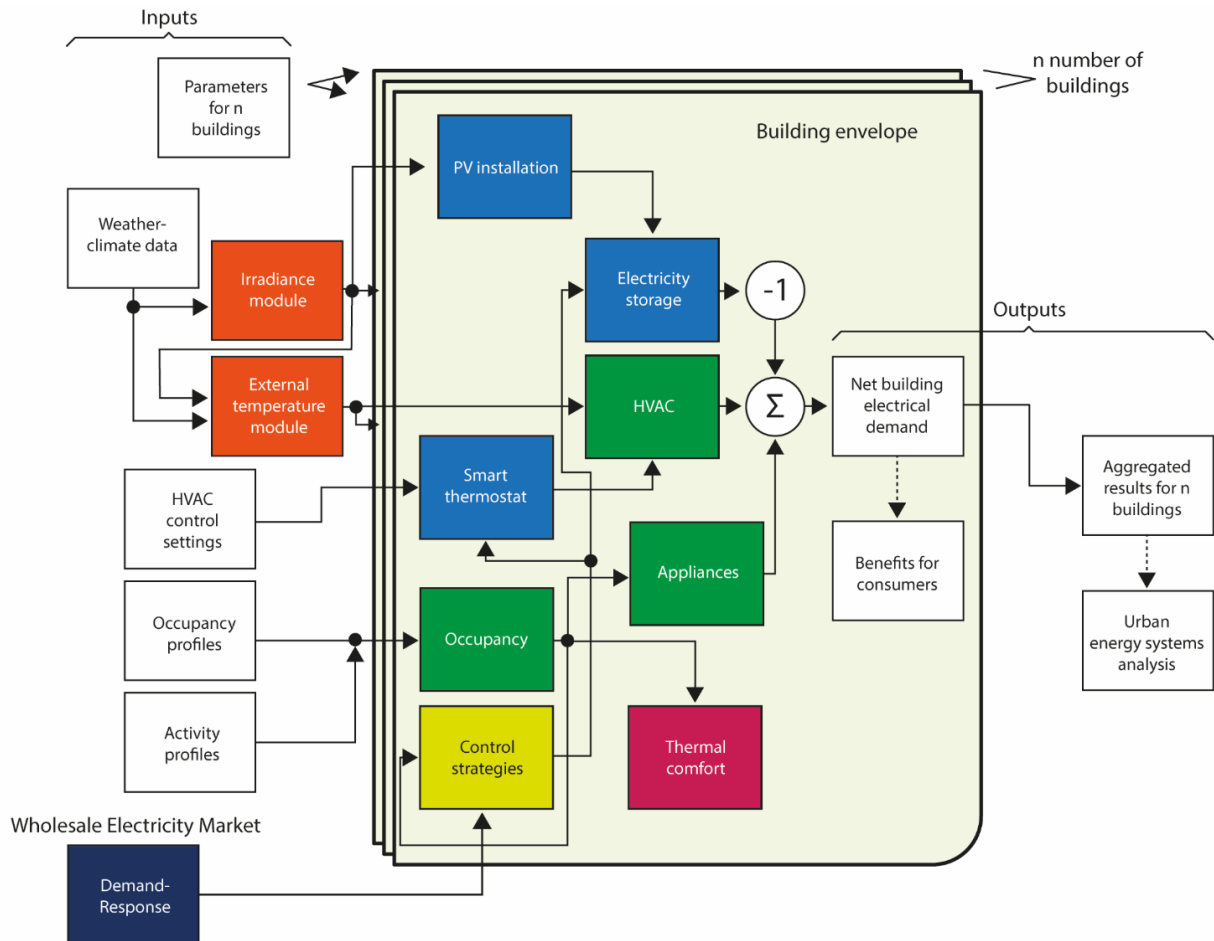
### 5.2.3 Linking QTDIAN and DREEM

#### 5.2.3.1 Description of DREEM

The **D**ynamic high-**R**esolution **d**emand-side **E**nergy **M**anagement (DREEM) model is a hybrid bottom-up model that combines key features of both statistical and engineering models. The model serves as an entry point in Demand-Side Management (DSM) modelling in the building sector, by expanding the computational capabilities of existing Building Energy System (BES) models by, not only calculating energy demand, but also assessing the benefits and limitations of demand flexibility, primarily for consumers as well as for other power actors involved (Stavrakas and Flamos, 2020). The novelty of the DREEM model lies mainly in its modularity, as its structure is decomposed into individual modules characterised by the main principles of component-/ modular-based systems modelling approach, namely “the interdependence of decisions within modules; the independence of decisions between modules; and the hierarchical dependence of modules on components embodying standards and design rules” (Pereverza et al., 2019) (**Figure 32**). This modular approach allows for more flexibility in terms of possible system configurations and computational efficiency towards a wide range of scenarios, studying different aspects of end-use.

The modular structure of the DREEM model allows for a wide range of functionalities regarding different decarbonisation scenarios in the European building stock. Next to calculating energy demand, such scenarios could also enable the evaluation of the performance and replicability potential of conventional and innovative energy-efficiency measures, in terms of their long-term energy savings, sustainability, risk, and return of investment. Such an evaluation would focus on assessing the potential benefits of each measure at a disaggregated (i.e., households-neighbourhood) level, and then allowing for upscaling at a national level. However, considering the role that the human factor is expected to play in these scenarios, it is important that socio-political aspects are incorporated into the model, to better ground model assumptions and to constrain otherwise free variables to reasonable ranges. In this regard, a

synergy with QTDIAN allows for more accurate parameterisation of the model than otherwise. This could also ensure that the model and its results represent energy transition pathways that are aligned with broader social storylines.



**Figure 32:** The DREEM model's architecture as it currently stands. Source: Stavrakas and Flamos, 2020.

### 5.2.3.2 Method to link QTDIAN with DREEM

**Figure 31** shows how linking QTDIAN and DREEM would shape our understanding of energy transition pathways between an understanding of social storylines, both qualitative and quantitative. The main idea is that quantitative data for three social storylines will be taken from QTDIAN and will be used as inputs to parameterise the DREEM model. DREEM will be then used to model the energy transition for each storyline in the residential sector in Greece by 2050 for the different values of the storyline variables presented in **Table 32**. A different mix of energy efficiency measures (in terms of deep renovation) and technologies for heating and cooling (i.e., natural gas boilers, heat pumps, air-conditioning units) will be tested in accordance with the specifications of the transition scenarios presented by (Vassilis Stavrakas et al., 2021). Indicative, final results will include final energy consumption per type of fuel, total energy savings due to renovation, total fuel savings due to renovation, tonnes of CO<sub>2</sub> avoided, economic benefits for households, etc. In addition, considering

recent developments of energy and climate laws, DREEM will also quantify potential implications for households from the extension of the emission trading scheme (ETS) to the residential sector for different feasible values of the carbon price. Finally, results from DREEM will be filtered based on the qualitative components of QTDIAN’s storylines to select a subset of feasible technological configurations that best represent each storyline.

**Table 32:** Storyline variables and quantifications for energy demand modelling with DREEM in the Greek residential sector. Source: (Süsser et al., 2021c)

Storyline variables & values	People-powered	Government-directed	Market-driven
Building renovation (residential, floor space)	Deep renovation rate of 0.2% annually; medium renovation of 1.1%	Deep renovation rate of 2.1% annually, 0.9% medium renovation	Deep renovate rate of 3% annually
Total floor area of single- & multi-family dwellings	Single: 160792.9 mm <sup>2</sup> (2016) Multi: 212390.53 mm <sup>2</sup> (2016)	Single: increase by 0.2% annually Multi: increase by 0.09% annually	Single: increase by 0.4% annually Multi: increase by 0.2% annually
Private electricity consumption of appliances and lighting	Linear decrease as of today	Exponential decrease to meet the 2030 target	Constant

### 5.2.2.3 Linkage challenges and possible benefits

Not all elements of the storylines given in **Table 2** can be incorporated into DREEM. This is due to the difficulty of quantifying all the different aspects of the storylines and the model’s structure, which doesn’t allow for the inclusion of the storyline variable “Rooms per person.” In addition, since the focus of the model is in the residential sector, the storyline variables “Electric vehicles” and “Travelled distances” can also not be incorporated. **Table 32: Storyline variables and quantifications for energy demand modelling with DREEM in the Greek residential sector.** **Table 32** represents the storyline inputs that can be realistically used by the model and for which there is no particular challenge, since these variables are already model inputs. On the other hand, since DREEM allows for greater sophistication with the integration of complex dynamics of the building stock transformations into the modelling process, it provides the capability to adopt a more interdisciplinary approach, encompassing the inclusion of socioeconomic and demographic factors. This could lead to parameterisation areas that may not be provided by QTDIAN at present. For example, in the context of the modelling exercises described above, DREEM will explore aspects of energy poverty in the residential sector by considering particularities of energy poor households. In addition, DREEM can also be parameterised to reflect on the dependence of energy consumption to individual behaviour towards better-informed policymaking that motivates people to regulate their energy consumption as a way to benefit financially from obtaining energy saving practices. These are potential synergies with QTDIAN that need to be further investigated.

## 6 Discussion and conclusion

Social and political issues are critical aspects of the energy transition and are at least as important determinants of the transition as economic and technical issues. For example, although wind energy is often the cheapest new source of electricity available, deployment has stalled in several parts of Europe due to public opposition to projects. As current models cannot usually adequately represent such aspects, they are often ignored, which severely compromises the usefulness of the results: Because pure techno-economic optimisation ignores a factor that so strongly determines actual deployment, the result describes a reality that has little to do with observed reality. The QTIDIAN toolbox is a step towards incorporating social and political factors into energy models in order to tie the models closer to reality and increase the usefulness of the models for the various model users, in politics, industry and society.

This report version 2 makes **three major contributions** to the SENTINEL project, and modelling work beyond:

- 1) Social storylines, based on transitions theory and empirical observation of actual social/political drivers and barriers in the European energy transition.
- 2) Quantitative, empirical data for a range of key social/political parameter, to be used in conjunction with the storylines for which we provide suggested data modifications, adapting the empirically observed “today” data according to the logics of the storylines. Furthermore, they can be used adapted in the way modellers see as appropriate for their scenarios and research questions.
- 3) Concrete examples of the conceptual linkages between QTIDIAN and Euro-Calliope, QTIDIAN, Euro-Calliope and WEGDYN, QTIDIAN and HEB, QTIDIAN and DESSTINEE, and QTIDIAN and DREEM.

A main contribution is that we present plausible (because actual, empirically observed) data for these variables, so that modellers can make their scenarios close to reality and not have to guess how important a societal/political factor may be; e.g. is a transmission line project delayed by 3 months, 3 or 10 years? or is the potential for citizen energy in the EU 5%, 20% or 50% of installed capacity?

Another contribution is the storylines, which are tied to the governance narratives of WHY a transition may happen (*the process*) and HOW the final system may look (*the outcome*). This is different from most other storyline approaches that tend to use external factors (e.g., global cooperation or competition; fast or slow tech progress, etc). This allows us to tie models and scenarios closer to the social and political realities that control actual transition pathways, allowing for an embedding in data and thinking outside the techno-economics that is already strongly represented in the models. In this report, we propose storyline quantifications that are ready to be plugged into energy models, in SENTINEL but in principle also beyond. These quantifications reflect the ideal-typical logics of the storylines and have been developed to be consistent and sufficiently distinct from another. However, they are not one-size-fits-all data, and it is possible to mix assumptions to create different storylines and pathways to test the significance of particular political or social developments. It is equally possible to use the raw data to create other social or political storylines: QTIDIAN is a toolbox, ready for different applications and adaptable to the specific needs of its users.

The third contribution is that we demonstrate concrete examples how the QTDIAN storylines and quantifications have been conceptually linked to the energy demand models DESSTINEE, HED and DREEM and the energy systems model Euro-Calliope. Linking QTDIAN with energy system and energy demand models allowed for a better representation of the socio-political drivers and barriers for technology changes and climate change mitigation measures, contributing to understanding how peoples' preferences, market conditions and policy frameworks can influence and lead to different service demand growth rates, fuel baskets, efficiency improvement trajectories, designs of energy landscapes, among others. The output data from QTDIAN provide updated values or values for indicators for which no data were available. Thus, it reduces the extent to which modellers use their own assumptions to constrain a future energy system and offers a concrete way for social scientists to feed findings into models through a new interdisciplinary link that is generally underdeveloped or inexistant. QTDIAN storylines also ensure that modellers do not create technically feasible energy systems that are outside the realms of reality. Unlike other social-political storylines, the inclusion of QTDIAN's quantified variables enable direct application of storylines into the modelling process, rather than relying on modeller interpretation or only bringing social-political aspects when discussing model outputs.

The data and storylines of QTIDIAN also come with some limitations and caveats. First, the numerical values of some variables and assumptions have been extrapolated from limited datasets. This results from a challenge of data availability, especially in different socio-political contexts. Second, although the storyline quantifications are closely tied to the logics underpinning the storylines, this is not an exact science. For example, for transmission opposition, we add or subtract 50% litigation share and delay time from the historically observed values, but there is no compelling reason to choose 50% over, say, 30% or 70%. The quantifications are thus constructed to reflect the logic while also making defensible and maximally different assumptions across the storylines. To allow modellers to make their own assumptions, and to self-assess the usefulness of the storyline quantifications, we also publish the raw historical observation data for each variable. Third, although we present the most recent data available, the half-life of some data may be short and may in some cases already be outdated. For example, national 2030 and 2050 GHG and renewable energy targets are based on the old EU climate (-40%) and energy targets and do not yet reflect the increased EU targets of 55% GHG reduction by 2030 and climate neutrality by 2050. If updated national targets become available before the end of the SENTINEL project, we will include them in future updates of QTIDIAN.

Further challenges emerged when linking the QTDIAN with energy models, including the expected observations that not all aspects of the storylines could be quantified, and that the models to which QTDIAN links in this deliverable are not able to capitalise on all QTDIAN outputs. First, certain social and behavioural aspects, such as people's attitudes and lifestyles, can hardly if not impossibly be expressed in numbers. If social scientific data are available, then they are generally specific for a country or region and rarely for all countries in Europe, and they are often not available as panel data to account for changes over time. A better availability of survey data on social and political aspects of the energy transition could substantially improve modelling efforts, as could the availability of data on regulations, which is currently very difficult to obtain for more than single countries and years. Second, the models are often not formulated ways allowing for easy inclusion of technology preferences and behavioural changes. For example, Euro-Calliope cannot explicitly define merit-order assumptions on technology

deployment, and thus, e.g., 'rooftop PV is always chosen in preference to open-field PV'. Other energy system models may be better placed to include these aspects of QTDIAN. In addition, by modelling fixed years (e.g., 2030, 2040, 2050), the three supply/ demand models to which QTDIAN links here are unable to capitalise on aspects of storylines that set limits through time (e.g., maximum annual deployment rates, etc.), or deadlines that occur in years that are not modelled (e.g., phase-out of a technology by 2034, etc.). Furthermore, different challenges emerged by integrating different QTDIAN outputs, regarding data comparability and data availability (temporal and spatial scales).

We identified further demands for assumptions and data, which cannot be met by the current QTDIAN version. Being able to have a higher geographical level of detail, country or group of countries, would be beneficial for QTDIAN and for the energy demand and supply models within the SENTINEL consortium, which estimates rely on behavioural and societal changes. Nevertheless, new demands for QTDIAN emerged in the linkage process, which could be partially already met via the updated data sets (ZENODO Version 2, (Süsser et al., 2022a)). Furthermore, there are final energy uses not covered by QTDIAN, but for which behavioural aspects are also important – such as passenger rail, aviation, and navigation – when focussing on individuals. Empirical data are needed for the evolution of the travelled distance and possible trends in modal shifts. Another step forward in QTDIAN development could be to incorporate variables related to the preferences of the business sector, which will influence energy consumption for commercial buildings, industries, and freight transport.

In this report, we presented the conceptual linkages between QTDIAN and Euro-Calliope, QTDIAN and HEB, QTDIAN and DESSTINEE, and QTDIAN and DREEM. We have run, or currently run (November 2022), the energy system and energy demand models with the integrated interlinkage with QTDIAN to evaluate the outcomes and added value of the interlinkage. We are specifically interested in the changes in the modelling results due to the integration of social and political aspects in the models, and to understand what input parameters have the highest impact on the observed changes.

We conclude that linking the QTDIAN modelling toolbox with energy demand and system models has contributed to a more decision-relevant modelling approach that takes social and political aspects of the energy transition better into account. As a result, the SENTINEL modelling framework will provide a set of more realistic pathways to achieve climate neutrality in the EU by 2050.

## References

- ACER, 2020. Consolidated report on the progress of electricity and gas Projects of Common Interest.
- AEE, 2017. Erneuerbare Energien in Bürgerhand.
- Auer, H., del Granado, P.C., Backe, S., Piscicella, P., Hainsch, K., 2019. Storylines for Low Carbon Futures of the European Energy System. Deliverable 7.1.
- Auer, H., del Granado, P.C., Huppmann, D., Oei, P., Hainsch, K., Löffler, K., Burandt, T., 2020. Quantitative Scenarios for Low Carbon Futures of the pan-European Energy System. Deliverable 3.1.
- Bachner, G., Kleanthis, N., Lackner, T., Mayer, J., Michas, S., Savelsberg, C., Sgarlato, R., Steininger, K.W., 2021. D5.3. Integration of market and economic model results into transition and energy demand models. Deliverable of the H2020 SENTINEL project.
- Barton, J., Davies, L., Dooley, B., Foxon, T.J., Galloway, S., Hammond, G.P., O'Grady, Á., Robertson, E., Thomson, M., 2018. Transition pathways for a UK low-carbon electricity system: Comparing scenarios and technology implications. *Renew. Sustain. Energy Rev.* 82, 2779–2790. <https://doi.org/10.1016/j.rser.2017.10.007>
- Bauwens, T., Devine-Wright, P., 2018. Positive energies? An empirical study of community energy participation and attitudes to renewable energy. *Energy Policy* 118, 612–625. <https://doi.org/10.1016/j.enpol.2018.03.062>
- Bolwig, S., Bolkesjø, T.F., Klitkou, A., Lund, P.D., Bergaentzlé, C., Borch, K., Olsen, O.J., Kirkerud, J.G., Chen, Y., Gunkel, P.A., 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 Res. Soc. Sci.* 67, 101559. <https://doi.org/10.1016/j.erss.2020.101559>
- Boßmann, T., Staffell, I., 2015. The shape of future electricity demand: Exploring load curves in 2050s Germany and Britain. *Energy* 90, 1317–1333. <https://doi.org/10.1016/j.energy.2015.06.082>
- Boudet, H.S., 2019. Public perceptions of and responses to new energy technologies. *Nat. Energy* 4, 446–455. <https://doi.org/10.1038/s41560-019-0399-x>
- Bridge, G., Gailing, L., 2020. New energy spaces: Towards a geographical political economy of energy transition. *Environ. Plan. A Econ. Sp.* 52, 1037–1050. <https://doi.org/10.1177/0308518X20939570>
- Brown, D., Hall, S., Davis, M.E., 2020. What is prosumerism for? Exploring the normative dimensions of decentralised energy transitions. *Energy Res. Soc. Sci.* 66, 101475. <https://doi.org/10.1016/j.erss.2020.101475>
- Bundesregierung, 2021. Gesetz für den Ausbau erneuerbarer Energien (ErneuerbareEnergien-Gesetz - EEG 2021).
- CAN Europe, ZERO, 2020. Pave the Way for Increased Climate Ambition.
- Cashmore, M., Rudolph, D., Larsen, S.V., Nielsen, H., 2019. International experiences with opposition to wind energy siting decisions: lessons for environmental and social appraisal. *J. Environ. Plan. Manag.* 62, 1109–1132. <https://doi.org/10.1080/09640568.2018.1473150>
- Ceglaz, A., Beneking, A., Ellenbeck, S., Battaglini, A., 2017. Understanding the role of trust in power line development projects: Evidence from two case studies in Norway. *Energy Policy* 110, 570–580. <https://doi.org/10.1016/j.enpol.2017.08.051>
- Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E., Sovacool, B., 2018. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Res. Soc. Sci.* 37, 175–190. <https://doi.org/10.1016/j.erss.2017.09.015>
- Climate Action Network Europe, European Environmental Bureau, 2020. Building a Paris Agreement Compatible (PAC) energy scenario: CAN Europe/EEB technical summary of key elements.
- Cohen, J.J., Reichl, J., Schmidthaler, M., 2014. Re-focussing research efforts on the public acceptance

- of energy infrastructure: A critical review. *Energy* 76, 4–9.  
<https://doi.org/10.1016/j.energy.2013.12.056>
- Dalla-Longa, F., Kober, T., Badger, J., Volker, P., Hoyer-Klcik, C., Hidalgo Gonzalez, I., Medarac, H., Nijs, W., Polities, S., Tarvydas, D., Zucker, A., 2018. Wind potentials for EU and neighbouring countries - Input datasets for the JRC-EU-TIMES Model. <https://doi.org/10.2760/041705>
- Danish Ministry of Climate, Energy and Utilities, 2019. Denmark's Integrated National Energy and Climate Plan.
- De Cian, E., Dasgupta, S., Hof, A.F., van Sluisveld, M., Köhler, J., Pfluger, B., van Vuuren, D.P., 2018. Actors, decision-making, and institutions in quantitative system modelling. *Technol. Forecast. Soc. Change* 151, 119480. <https://doi.org/10.1016/j.techfore.2018.10.004>
- Degel, M., Christ, M., Becker, L., Grünert, J., 2016. Sozial-ökologische und technisch-ökonomische Modellierung von Entwicklungspfaden der Energiewende. Berlin.
- del Granado, P.C., et al., 2019. Comparative Assessment and Analysis of SET-Nav Pathways. A Rep. Compil. within SET-Nav Proj. - Work Packag. 9, Task 9.4, D9.4 691843, 1–35.
- Devine-Wright, P., 2007. Reconsidering public attitudes and public acceptance of renewable energy technologies : a critical review.
- Devine-Wright, P., Howes, Y., 2010. Disruption to place attachment and the protection of restorative environments: A wind energy case study. *J. Environ. Psychol.* 30, 271–280.  
<https://doi.org/10.1016/j.jenvp.2010.01.008>
- DGRV, 2020. DGRV-Jahresumfrage Energiegenossenschaften 2020.
- Dietz, M., Garrelts, H. (Eds.), 2014. *Routledge Handbook of the Climate Change Movement*, 1st editio. ed. Routledge.
- Directorate-General for Energy (European Commission), Ipsos Belgium, Navigant, 2019. Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU - Final report. <https://doi.org/10.2833/14675>
- Ellenbeck, S., Lilliestam, J., 2019. How modelers construct energy costs: Discursive elements in Energy System and Integrated Assessment Models. *Energy Res. Soc. Sci.* 47, 69–77.  
<https://doi.org/10.1016/j.erss.2018.08.021>
- Energy Community Secretary, 2021. Electricity Interconnection Targets in the Energy Community Contracting Parties.
- ENTSO-E, 2021a. Ten-Year Network Development Plan 2020.
- ENTSO-E, 2021b. TYNDP 2020 Projects Sheets.
- ENTSO-E, 2012. 10-Year Network Development Plan 2012. Report 1–219.
- Europe Beyond Coal, 2021. Europe's coal exit overview of national coal phase out commitments.
- European Commission, 2020. A hydrogen strategy for a climate-neutral Europe. *Eur. Comm.* 24.
- European Commission, 2021a. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. "Fit for 55": delivering the EU's 2030 Climate Target on the way to climate neutrality. Brussels, Belgium.
- European Commission, 2021b. EU reference scenario 2020: Energy, transport and GHG emissions - Trends to 2050. Publications Office of the European Union, Luxembourg.  
<https://doi.org/10.2833/35750>
- European Commission, 2020a. Just Transition Platform. Accompanying Member States and regions to achieve a just transition. [WWW Document].
- European Commission, 2020b. Impact Assessment, accompanying Communication 'Stepping up Europe's 2030 climate ambition - Investing in a climate-neutral future for the benefit of our people. SWD - Staff Jt. Work. Doc. Eur. Comm.
- European Commission, 2019a. Special Eurobarometer 490 Climate Change.  
<https://doi.org/10.2834/00469>

- European Commission, 2019b. Special Eurobarometer 492: European's attitudes on EU energy policy. Eurobarometer.
- European Commission, 2019c. The European Green Deal. <https://doi.org/10.1128/AAC.03728-14>
- European Commission, 2019d. The European Green Deal. Eur. Comm. <https://doi.org/10.1017/CBO9781107415324.004>
- European Commission, 2018. SET plan delivering results: The implementation plans. Research & innovation enabling the EU's energy transition. Publications Office of the European Union, Luxembourg. <https://doi.org/10.2833/109890>
- European Commission, 2016. EU Reference Scenario 2016 27. <https://doi.org/10.2833/9127>
- European Commission, 2011. Energy roadmap 2050: COM(2011) 885. Brussels.
- Eurostat, 2021. Electricity production capacities by main fuel groups and operator.
- Fast, S., 2013. Social acceptance of renewable energy: Trends, concepts, and geographies. *Geogr. Compass* 7, 853–866. <https://doi.org/10.1111/gec3.12086>
- Fortes, P., Alvarenga, A., Seixas, J., Rodrigues, S., 2015. Long-term energy scenarios: Bridging the gap between socio-economic storylines and energy modeling. *Technol. Forecast. Soc. Change* 91, 161–178. <https://doi.org/10.1016/j.techfore.2014.02.006>
- 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. *Technol. Forecast. Soc. Change* 77, 1203–1213. <https://doi.org/10.1016/j.techfore.2010.04.002>
- Gaschnig, H., Süsser, D., Ceglarz, A., Stavrakas, V., Giannakidis, G., Flamos, A., Sander, A., 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. Eur. Comm. Inst. Adv. Sustain. Stud. (IASS), Potsdam.
- Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. *Res. Policy* 31, 1257–1274. [https://doi.org/10.1016/S0048-7333\(02\)00062-8](https://doi.org/10.1016/S0048-7333(02)00062-8)
- Geels, F.W., Berkhout, F., Van Vuuren, D.P., 2016. Bridging analytical approaches for low-carbon transitions. *Nat. Clim. Chang.* 6, 576–583. <https://doi.org/10.1038/nclimate2980>
- Geels, F.W., Sovacool, B., Schwanen, T., Sorrell, S., 2017. Sociotechnical transitions for deep decarbonization: Accelerating innovation is as important as climate policy. *Science (80-. )*. 357, 1242–1244. <https://doi.org/10.1126/science.aao3760>
- Gerhards, C.; Weber, U.; Klafka, P; Golla, S., 2021. Klimaverträgliche Energie- versorgung für Deutschland, Diskussionsbeiträge der Scientists for Future, 7 1–55. <https://doi.org/10.5281/zenodo.4409334>
- Halbe, J., Reusser, D.E., Holtz, G., Haasnoot, M., Stosius, A., Avenhaus, W., Kwakkel, J.H., 2015. Lessons for model use in transition research: A survey and comparison with other research areas. *Environ. Innov. Soc. Transitions* 15, 194–210. <https://doi.org/10.1016/j.eist.2014.10.001>
- HELLENIC REPUBLIC Ministry of the Environment and Energy, 2019. National Energy and Climate Plan, Greece. Athens.
- Hewitt, R.J., Bradley, N., Baggio Compagnucci, A., Barlagne, C., Ceglarz, A., Cremades, R., McKeen, M., Otto, I.M., Slee, B., 2019. Social Innovation in Community Energy in Europe: A Review of the Evidence. *Front. Energy Res.* 7. <https://doi.org/10.3389/fenrg.2019.00031>
- HIER climate foundation, RVO, 2020. Lokale Energie Monitor.
- Hirt, Léon F., Schell, G., Sahakian, M., Trutnevyte, E., 2020. A review of linking models and socio-technical transitions theories for energy and climate solutions. *Environ. Innov. Soc. Transitions* 35, 162–179. <https://doi.org/10.1016/j.eist.2020.03.002>
- Hirt, Léon F., Schell, G., Sahakian, M., Trutnevyte, E., 2020. A review of linking models and socio-

- technical transitions theories for energy and climate solutions. *Environ. Innov. Soc. Transitions* 35, 162–179. <https://doi.org/10.1016/j.eist.2020.03.002>
- Hof, A.F., Carrara, S., De Cian, E., Pfluger, B., van Sluisveld, M., de Boer, H.S., van Vuuren, D.P., 2020. From global to national scenarios: Bridging different models to explore power generation decarbonisation based on insights from socio-technical transition case studies. *Technol. Forecast. Soc. Change* 151, 119882. <https://doi.org/10.1016/j.techfore.2019.119882>
- Holtz, G., Alkemade, F., de Haan, F., Köhler, J., Trutnevyte, E., Luthe, T., Halbe, J., Papachristos, G., Chappin, E., Kwakkel, J., Ruutu, S., 2015. Prospects of modelling societal transitions: Position paper of an emerging community. *Environ. Innov. Soc. Transitions* 17, 41–58. <https://doi.org/10.1016/j.eist.2015.05.006>
- IEA, 2022. *Global EV Outlook 2022. Securing supplies for an electric future* 221.
- IEA, 2021a. *Global EV Data Explorer*.
- IEA, 2021b. *Global EV outlook 2021*. International Energy Agency, Paris.
- IEA, 2021c. *Global EV outlook 2021*. International Energy Agency, Paris.
- 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. <https://doi.org/10.1016/j.enpol.2019.111212>
- Kahla, F., Lars, H., Müller, J.R., Degenhart, H., 2017. *Entwicklung und Stand von Bürgerenergiegesellschaften und Energiegenossenschaften in Deutschland* 37.
- Kaldellis, J.K., Kapsali, M., Kaldelli, E., Katsanou, E., 2013. Comparing recent views of public attitude on wind energy, photovoltaic and small hydro applications. *Renew. Energy* 52, 197–208. <https://doi.org/10.1016/j.renene.2012.10.045>
- Kampman, B., Blommerde, J., Afma, M., 2016. *The potential of energy citizens in the European Union [Report commissioned by Greenpeace]*.
- Kaplan, U.E., Topal, E., 2020. A new ore grade estimation using combine machine learning algorithms. *Minerals* 10, 847. <https://doi.org/10.3390/min10100847>
- Koppelaar, R.H.E.M., Keirstead, J., Shah, N., Woods, J., 2016. A review of policy analysis purpose and capabilities of electricity system models. *Renew. Sustain. Energy Rev.* 59, 1531–1544. <https://doi.org/10.1016/j.rser.2016.01.090>
- Krumm, A., Süsner, D., Blechinger, P., 2022. Modelling social aspects of the energy transition: What is the current representation of social factors in energy models? *Energy* 239, 121706. <https://doi.org/10.1016/j.energy.2021.121706>
- Li, F.G.N., Trutnevyte, E., Strachan, N., 2015. A review of socio-technical energy transition STET models. *Technol. Forecast. Soc. Change* 100, 290–305. <https://doi.org/10.1016/j.techfore.2015.07.017>
- Lilliestam, J., Ollier, L., Labordena, M., Pfenninger, S., Thonig, R., 2021. The near- to mid-term outlook for concentrating solar power: mostly cloudy, chance of sun. *Energy Sources, Part B Econ. Plan. Policy* 16, 23–41. <https://doi.org/10.1080/15567249.2020.1773580>
- Lilliestam, J., Ollier, L., Thonig, R., Del Río, P., Kiefer, C., Caldés, N., Lechón, Y., Escribano, G., Lázaro Touza, L., 2019. Policy pathways for the energy transition in Europe and selected European countries ) 154.
- Lombardi, F., Pickering, B., Colombo, E., Pfenninger, S., 2020. Policy Decision Support for Renewables Deployment through Spatially Explicit Practically Optimal Alternatives. *Joule* 4, 2185–2207. <https://doi.org/10.1016/j.joule.2020.08.002>
- Lombardi, F., Rocco, M.V., Colombo, E., 2019. A multi-layer energy modelling methodology to assess the impact of heat-electricity integration strategies: The case of the residential cooking sector in Italy. *Energy* 170, 1249–1260. <https://doi.org/10.1016/j.energy.2019.01.004>
- Lopion, P., Markewitz, P., Robinius, M., Stolten, D., 2018. A review of current challenges and trends in energy systems modeling. *Renew. Sustain. Energy Rev.* 96, 156–166.

- <https://doi.org/10.1016/j.rser.2018.07.045>
- Loulou, R., Labriet, M., 2008. ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. *Comput. Manag. Sci.* 5, 7–40. <https://doi.org/10.1007/s10287-007-0046-z>
- Madrid-López, C., Süsser, D., Stavrakas, V., Lilliestam, J., Flamos, A., Peiró, L.T., Martin, N., 2021. Model development to match ENBIOS, QTDIAN and ATOM to user needs. Deliverable 2.4., Sustainable Energy Transitions Laboratory (SENTINEL) project.
- Martin, N., Madrid-López, C., Talens-Peiró, L., Süsser, D., Gaschnig, H., Lilliestam, J., 2020. Observed trends and modelling paradigms on the social and environmental aspects of the energy transition. Deliverable 2.1.
- McGookin, C., Mac Uidhir, T., Ó Gallachóir, B., Byrne, E., 2022. Doing things differently: Bridging community concerns and energy system modelling with a transdisciplinary approach in rural Ireland. *Energy Res. Soc. Sci.* 89, 102658. <https://doi.org/10.1016/j.erss.2022.102658>
- McGookin, C., Ó Gallachóir, B., Byrne, E., 2021. Participatory methods in energy system modelling and planning – A review. *Renew. Sustain. Energy Rev.* 151, 111504. <https://doi.org/10.1016/j.rser.2021.111504>
- Michas, S., Kleanthis, N., Stavrakas, V., Schibline, A., Ceglaz, A., Flamos, A., Al., E., 2022. Model application in the case studies: challenges and lessons learnt. Deliverable 7.2. Sustainable Energy Transitions Laboratory (SENTINEL) project. Piraeus, Greece.
- Michas, S., Stavrakas, V., Papadelis, S., Flamos, A., 2020. A transdisciplinary modeling framework for the participatory design of dynamic adaptive policy pathways. *Energy Policy* 139, 111350. <https://doi.org/10.1016/j.enpol.2020.111350>
- Miller, C.A., Iles, A., Jones, C.F., 2013. The Social Dimensions of Energy Transitions. *Sci. Cult. (Lond.)* 22, 135–148. <https://doi.org/10.1080/09505431.2013.786989>
- Ministry for the Environment and Natural Resources, 2018. Iceland's Climate Action Plan for 2018-2030.
- Ministry of Economic Affairs and Employment, 2019. Finland's Integrated Energy and Climate Plan.
- Morgenthaler, S., Ball, C., Koj, J.C., Kuckshinrichs, W., Witthaut, D., 2020. Site-dependent levelized cost assessment for fully renewable Power-to-Methane systems. *Energy Convers. Manag.* 223, 113150. <https://doi.org/10.1016/j.enconman.2020.113150>
- Network for Transdisciplinarity Research, 2021. Three types of knowledge tool A tool for tailoring research questions to (societal) knowledge demands [WWW Document]. URL [https://naturalsciences.ch/co-producing-knowledge-explained/methods/td-net\\_toolbox/three\\_types\\_of\\_knowledge\\_tool](https://naturalsciences.ch/co-producing-knowledge-explained/methods/td-net_toolbox/three_types_of_knowledge_tool) (accessed 2.26.21).
- Norden and IEA, 2016. Nordic Energy Technology Perspectives 2016. Cities, flexibility and pathways to carbon-neutrality. Paris. <https://doi.org/10.1787/9789264257665-en>
- Nordic Energy Research, 2020. Progress towards Nordic carbon neutrality: Tracking Nordic clean energy progress 2020. Oslo.
- Norwegian Ministry of Climate and Environment, 2019. Norway's National Plan. related to the Decision of the EEA Joint Committee.
- O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Chang.* 42, 169–180. <https://doi.org/10.1016/j.gloenvcha.2015.01.004>
- O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Clim. Change* 122, 387–400. <https://doi.org/10.1007/s10584-013-0905-2>
- Oreggioni G D, S.I., n.d. Country level energy demand modelling in the context of Europe's 2030 and 2050 decarbonisation targets: A closer look at national challenges and opportunities. Prep.

- Overland, I., Sovacool, B.K., 2020. The misallocation of climate research funding. *Energy Res. Soc. Sci.* 62, 101349. <https://doi.org/10.1016/j.erss.2019.101349>
- Pereverza, K., Pasichnyi, O., Kordas, O., 2019. Modular participatory backcasting: A unifying framework for strategic planning in the heating sector. *Energy Policy* 124, 123–134. <https://doi.org/10.1016/j.enpol.2018.09.027>
- Petrichenko, K., 2014. *Net-Zero Energy Buildings: Global and Regional Perspectives*. Central European University, Budapest.
- Pfenninger, S., Hawkes, A., Keirstead, J., 2014. Energy systems modeling for twenty-first century energy challenges. *Renew. Sustain. Energy Rev.* 33, 74–86. <https://doi.org/10.1016/j.rser.2014.02.003>
- Pfenninger, S., Pickering, B., 2018. Calliope: A multi-scale energy systems modelling framework. *J. Open Source Softw.* 3, 825. <https://doi.org/10.21105/joss.00825>
- Pickering, B., Roelfsema, M., Mikropoulos, S., Chang, M., Thellufsen, J.Z., & van Vuuren, D., 2022. Model development to match system design models to user needs. Deliverable 4.2, Sustainable Energy Transitions Laboratory (SENTINEL) project.
- Pickering, B., Choudhary, R., 2021. Quantifying resilience in energy systems with out-of-sample testing. *Appl. Energy* 285, 116465. <https://doi.org/10.1016/j.apenergy.2021.116465>
- Pickering, B., Choudhary, R., 2019. District energy system optimisation under uncertain demand: Handling data-driven stochastic profiles. *Appl. Energy* 236, 1138–1157. <https://doi.org/10.1016/j.apenergy.2018.12.037>
- Pickering, B., Lombardi, F., Pfenninger, S., 2022. Diversity of options to eliminate fossil fuels and reach carbon neutrality across the entire European energy system. *Joule* 6, 1253–1276. <https://doi.org/10.1016/j.joule.2022.05.009>
- Pregger, T., Naegler, T., Weimer-Jehle, W., Prehofer, S., Hauser, W., 2019. Moving towards socio-technical scenarios of the German energy transition - Lessons learned from integrated energy scenario building. *Clim. Change*. <https://doi.org/10.1007/s10584-019-02598-0>
- Quentin, J., 2019. *Hemmnisse beim Ausbau der Windenergie in Deutschland. Ergebnisse einer Branchenumfrage zu Klagen gegen Windenergieanlagen sowie zu Genehmigungshemmnissen durch Drehfunkfeuer und militärische Belange der Luftraumnutzung*. Berlin.
- Renn, O., Wolf, I., Setton, D., 2020. *Soziales Nachhaltigkeitsbarometer der Energiewende*. <https://doi.org/https://doi.org/10.7802/2120>
- Resch, G., Schöniger, F., Kleinschmitt, C., Franke, K., Sensfuß, F., Thonig, R., Lilliestam, J., 2020. Market uptake of concentrating solar power in Europe: model-based analysis of drivers and policy trade-off. Deliverable 8.3 MUSTEC project, TU Wien, Wien.
- REScoop.eu & Friends of the Earth Europe, 2016. Potential for citizen-produced electricity in the EU 2–4.
- Reusswig, F., Braun, F., Heger, I., Ludewig, T., Eichenauer, E., Lass, W., 2016. Against the wind: Local opposition to the German Energiewende. *Util. Policy* 41, 214–227. <https://doi.org/10.1016/j.jup.2016.02.006>
- Ringler, P., Keles, D., Fichtner, W., 2016. Agent-based modelling and simulation of smart electricity grids and markets - A literature review. *Renew. Sustain. Energy Rev.* 57, 205–215. <https://doi.org/10.1016/j.rser.2015.12.169>
- Robertson, E., O'Grady, Á., Barton, J., Galloway, S., Emmanuel-Yusuf, D., Leach, M., Hammond, G., Thomson, M., Foxon, T., 2017. Reconciling qualitative storylines and quantitative descriptions: An iterative approach. *Technol. Forecast. Soc. Change* 118, 293–306. <https://doi.org/10.1016/j.techfore.2017.02.030>
- Rodrigues, R., Pietzcker, R., Fragkos, P., Price, J., McDowall, W., Siskos, P., Fotiou, T., Luderer, G., Capros, P., 2022. Narrative-driven alternative roads to achieve mid-century CO2 net neutrality in Europe. *Energy* 239, 121908. <https://doi.org/10.1016/j.energy.2021.121908>

- Rogers, J.C., Simmons, E.A., Convery, I., Weatherall, A., 2008. Public perceptions of opportunities for community-based renewable energy projects. *Energy Policy* 36, 4217–4226. <https://doi.org/10.1016/j.enpol.2008.07.028>
- Savvidou, G., Nykvist, B., 2020. Heat demand in the Swedish residential building stock - pathways on demand reduction potential based on socio-technical analysis. *Energy Policy* 144, 111679. <https://doi.org/10.1016/j.enpol.2020.111679>
- Schöniger, F., Resch, G., Kleinschmitt, C., Franke, K., Sensfuß, F., Lilliestam, J., Thonig, R., 2020. Pivotal decisions and key factors for robust CSP strategies. Deliverable 7.4, MUSTEC project.
- Setton, D., 2019. Soziales Nachhaltigkeitsbarometer der Energiewende 2018, Institut für transformative Nachhaltigkeitsforschung (IASS). <https://doi.org/10.2312/iass.2019.002>
- Sovacool, B.K., Hess, D.J., Cantoni, R., Lee, D., Claire Brisbois, M., Jakob Walnum, H., Freng Dale, R., Johnsen Rygg, B., Korsnes, M., Goswami, A., Kedia, S., Goel, S., 2022. Conflicted transitions: Exploring the actors, tactics, and outcomes of social opposition against energy infrastructure. *Glob. Environ. Chang.* 73, 102473. <https://doi.org/10.1016/j.gloenvcha.2022.102473>
- Squazzoni, F., 2010. THE IMPACT OF AGENT-BASED MODELS IN THE SOCIAL SCIENCES AFTER 15 YEARS OF INCURSIONS. *Hist. Econ. Ideas* 18, 197–234.
- Stavrakas, V., Ceglaz, A., Kleanthis, N., Giannakidis, G., Schibline, A., Süsser, D., Lilliestam, J., Flamos, A., 2021. Case specification and scheduling. Deliverable 7.1.
- Stavrakas, Vassilis, Ceglaz, A., Kleanthis, N., Giannakidis, G., Schibline, A., Süsser, D., Lilliestam, J., Psyri, A., Flamos, A., 2021. Case specification and scheduling. Deliverable 7.1. Sustainable Energy Transitions Laboratory (SENTINEL) project. <https://doi.org/10.5281/ZENODO.4699518>
- Stavrakas, V., Flamos, A., 2020. A modular high-resolution demand-side management model to quantify benefits of demand-flexibility in the residential sector. *Energy Convers. Manag.* 205, 112339. <https://doi.org/10.1016/j.enconman.2019.112339>
- Stavrakas, V., Papadelis, S., Flamos, A., 2019. An agent-based model to simulate technology adoption quantifying behavioural uncertainty of consumers. *Appl. Energy* 255, 113795. <https://doi.org/10.1016/j.apenergy.2019.113795>
- Süsser, D., al Rakouki, H., Lilliestam, J., 2022a. Data related to Süsser et al. (2021) QTDIAN modelling toolbox (Version 2) [Data set]. <https://doi.org/10.5281/zenodo.5834010>
- Süsser, D., Ceglaz, A., Gaschnig, H., Stavrakas, V., Flamos, A., Giannakidis, G., Lilliestam, J., 2021a. Model-based policymaking or policy-based modelling? How energy models and energy policy interact. *Energy Res. Soc. Sci.* 75, 101984. <https://doi.org/10.1016/j.erss.2021.101984>
- Süsser, D., Ceglaz, A., Stavrakas, V., Lilliestam, J., 2021b. Survey data related to the study Süsser et al (2021) “COVID-19 vs. stakeholder engagement: The impact of coronavirus containment measures on stakeholder involvement in European energy research projects” [Data set]. Zenodo. <https://doi.org/http://doi.org/10.5281/zenodo.4765630>
- Süsser, D., Gaschnig, H., Ceglaz, A., Stavrakas, V., Flamos, A., Lilliestam, J., 2022b. Better suited or just more complex? On the fit between user needs and modeller-driven improvements of energy system models. *Energy* 239, 121909. <https://doi.org/10.1016/j.energy.2021.121909>
- Süsser, D., Kannen, A., 2017. ‘Renewables? Yes, please!’: Perceptions and assessment of community transition induced by renewable-energy projects in North Frisia. *Sustain. Sci.* 12, 563–578. <https://doi.org/10.1007/s11625-017-0433-5>
- Süsser, D., Pickering, B., Chatterjee, S., Oreggioni, G., Stavrakas, V., Lilliestam, J., 2021c. Integration of socio-technological transition constraints into energy demand and systems models. *Sentin. Deliv.* 2.5 1–39. <https://doi.org/10.48481/iass.2021.030>
- The Ministry of Infrastructure, 2020. Sweden’s Integrated National Energy and Climate Plan.
- Thonig, R., Del Río, P., Kiefer, C., Lázaro Touza, L., Escribano, G., Lechón, Y., Späth, L., Wolf, I., Lilliestam, J., 2021. Does ideology influence the ambition level of climate and renewable energy policy? Insights from four European countries. *Energy Sources, Part B Econ. Planning, Policy* 16,

- 4–22. <https://doi.org/10.1080/15567249.2020.1811806>
- Tröndle, T., 2020. Supply-side options to reduce land requirements of fully renewable electricity in Europe. *PLoS One* 15, 1–19. <https://doi.org/10.1371/journal.pone.0236958>
- Tröndle, T., Lilliestam, J., Marelli, S., Pfenninger, S., 2020. Trade-Offs between Geographic Scale, Cost, and Infrastructure Requirements for Fully Renewable Electricity in Europe. *Joule* 4, 1929–1948. <https://doi.org/10.1016/j.joule.2020.07.018>
- Tröndle, T., Pfenninger, S., Lilliestam, J., 2019. Home-made or imported: On the possibility for renewable electricity autarky on all scales in Europe. *Energy Strateg. Rev.* 26, 100388. <https://doi.org/10.1016/j.esr.2019.100388>
- Trutnevyte, E., 2016. Does cost optimization approximate the real-world energy transition? *Energy* 106, 182–193. <https://doi.org/10.1016/j.energy.2016.03.038>
- Trutnevyte, E., Barton, J., O'Grady, Á., Ogunkunle, D., Pudjianto, D., Robertson, E., 2014. Linking a storyline with multiple models: A cross-scale study of the UK power system transition. *Technol. Forecast. Soc. Change* 89, 26–42. <https://doi.org/10.1016/j.techfore.2014.08.018>
- Trutnevyte, E., Hirt, L.F., Bauer, N., Cherp, A., Hawkes, A., Edelenbosch, O.Y., Pedde, S., van Vuuren, D.P., 2019. Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. *One Earth* 1, 423–433. <https://doi.org/10.1016/j.oneear.2019.12.002>
- Trutnevyte, E., Stauffacher, M., Scholz, R.W., 2011. Supporting energy initiatives in small communities by linking visions with energy scenarios and multi-criteria assessment. *Energy Policy* 39, 7884–7895. <https://doi.org/10.1016/j.enpol.2011.09.038>
- Turnheim, B., Berkhout, F., Geels, F., Hof, A., McMeekin, A., Nykvist, B., van Vuuren, D., 2015. Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Glob. Environ. Chang.* 35, 239–253. <https://doi.org/10.1016/j.gloenvcha.2015.08.010>
- Urge-Vorsatz, D., 2012. Best Practice Policies for Low Carbon & Energy Buildings Best Practice Policies for Low Carbon & Energy Buildings.
- van Sluisveld, M.A.E., Hof, A.F., Carrara, S., Geels, F.W., Nilsson, M., Rogge, K., Turnheim, B., van Vuuren, D.P., 2020. Aligning integrated assessment modelling with socio-technical transition insights: An application to low-carbon energy scenario analysis in Europe. *Technol. Forecast. Soc. Change* 151, 119177. <https://doi.org/10.1016/j.techfore.2017.10.024>
- Walker, B.J.A., Wiersma, B., Bailey, E., 2014. Community benefits, framing and the social acceptance of offshore wind farms: An experimental study in England. *Energy Res. Soc. Sci.* 3, 46–54. <https://doi.org/10.1016/j.erss.2014.07.003>
- Wolf, I., 2020. Soziales Nachhaltigkeitsbarometer der Energiewende 2019. *Inst. für Transform. Nachhalt.* 40. <https://doi.org/10.2312/iass.2020.010>
- Wüstenhagen, R., Wolsink, M., Bürer, M.J., 2007. Social acceptance of renewable energy innovation: An introduction to the concept. *Energy Policy* 35, 2683–2691. <https://doi.org/10.1016/j.enpol.2006.12.001>

## Appendix 1 Socially feasible scaling and decline of energy technologies

**Data availability.** We reviewed various datasets from different sources. Electricity generation capacity (Eurostat), the Energy Statistics Database (UN), renewable capacity statistics (IRENA), world energy statistics (IEA data on OECD library), statistical data sheets (ENTSO-E) and others. The Eurostat and UN databases were selected because the data are "open", the data are geographically and temporally comprehensive, they contain statistics for a wide range of renewable technologies, combustible fuels and total installed capacity. The UN database "contains basic statistics for more than 230 countries/territories from 1950 onwards". For a description of the Eurostat data used, see: [https://ec.europa.eu/eurostat/cache/metadata/en/nrg\\_inf\\_epc\\_esms.htm](https://ec.europa.eu/eurostat/cache/metadata/en/nrg_inf_epc_esms.htm)

**Limitations.** Both Eurostat and UN data sets are incomplete (sometimes missing or no available data). When capacity data was missing, we replaced it with zeros in the presentation in the bar charts. In addition, unstated or missing data have been omitted from the presentation of percentages and velocity figures. For example: for Turkey, Bosnia, Kosovo, Moldova, Ukraine and Georgia, capacity in 2019 is not indicated in the data, therefore the graph does not show 2019. Similarly, unstated or missing data is omitted when looking for minimum/maximum capacity in a country.

### Data analysis.

- 1) We calculated the speed of expansion or the capacity increase/decrease, i.e. the difference between each two cumulative installed capacity in GW. This gives the megawatt capacity added annually. This is done for the EU, the EU countries (Eurostat) and the countries of the world (UN data). The three countries with the greatest/highest/maximum rate of expansion or capacity growth are then taken as examples.
- 2) We calculated the difference between GW capacity for each of the five years (starting with 2019 and the five years before, then 2018 and the five years before, etc.). We then plotted the three countries with the largest/highest/maximum capacity change, regardless of which five years. We also calculated the difference between the percentage capacity for each of the five years. Then we plotted the three countries with the greatest/highest/maximum change in capacity, regardless of which five years. Using capacity as a percentage tells how much each county added/removed compared to its own total capacity, this allows for comparison between counties.
- 3) We then calculated the speed of introduction or capacity growth/decline, i.e. the difference between the two cumulative capacity as a percentage, and obtained a percentage capacity added each year (the system change in %). This is done for the EU, EU countries (Eurostat) and world countries (UN data/Irena). The three countries with the greatest/highest/maximum speed of adoption or capacity growth are then taken as examples. The calculation of the percentage capacity allows a comparison between countries.

The percentage is calculated as follows: The solar or wind or fuel GW capacity is multiplied by 100 and then divided by the total GW capacity of the same country for the same year. The result is the solar, wind and combustible capacity in percent. Each two consecutive percentages are then subtracted to get the system change in percent. (The result of the subtraction is assigned to the year

of the first subtracted term, in other words, the wind capacity in 2019 is subtracted from the wind capacity in 2018 and the subtraction result is assigned to 2019).

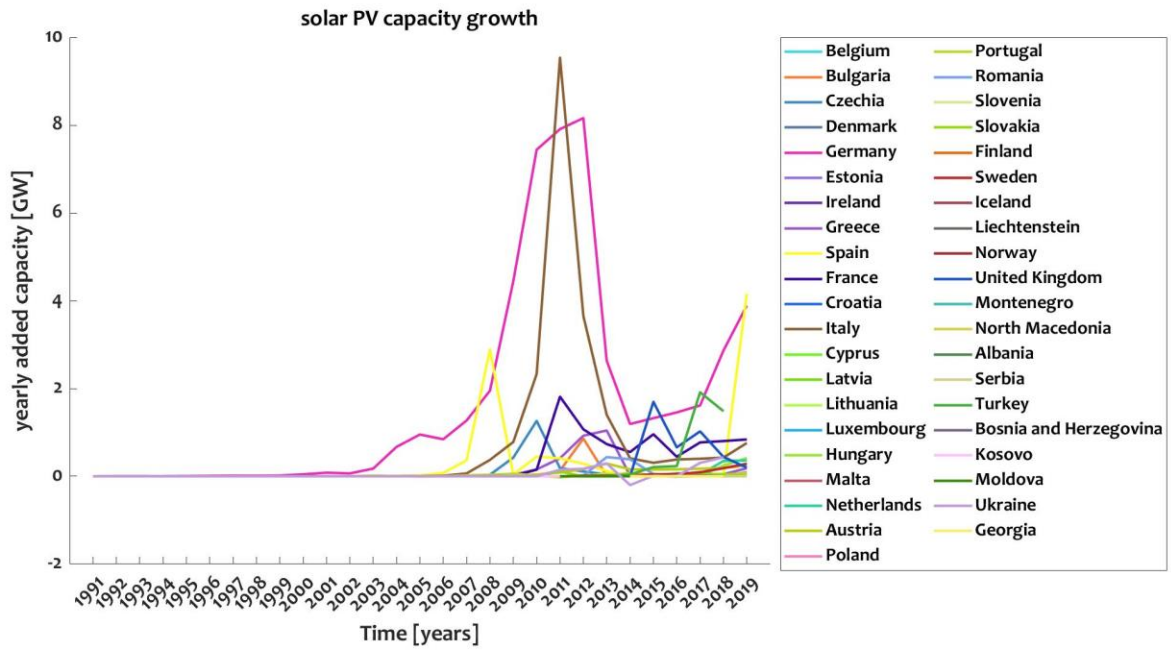


Figure A 1: Solar PV capacity growth.

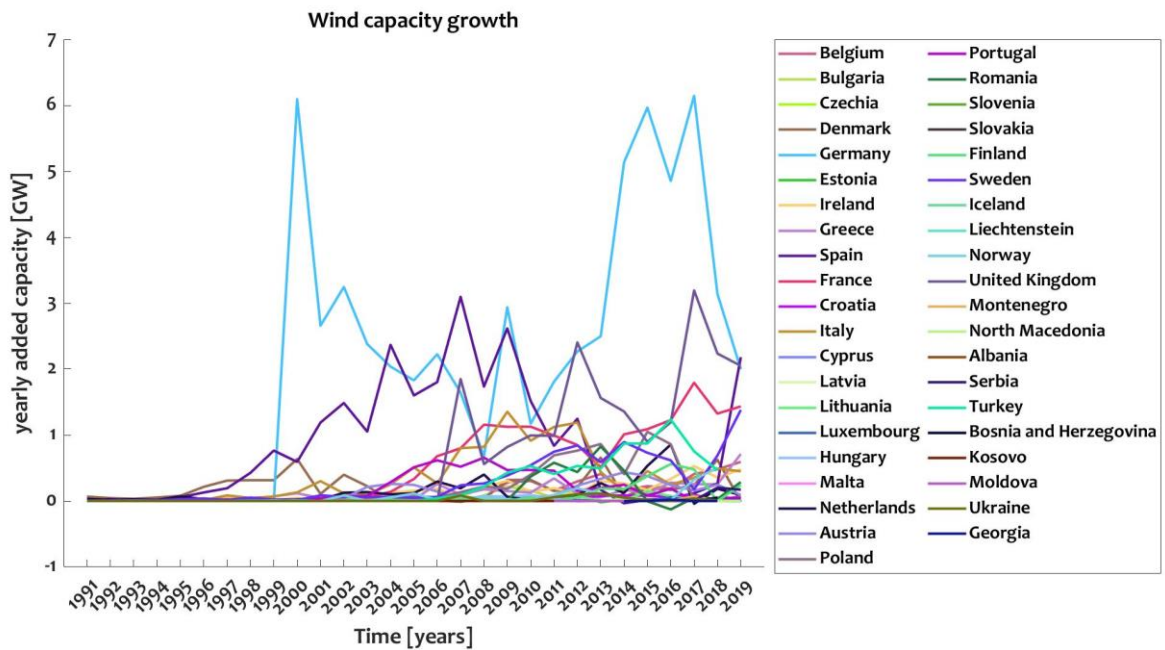


Figure A 2: Wind capacity growth.

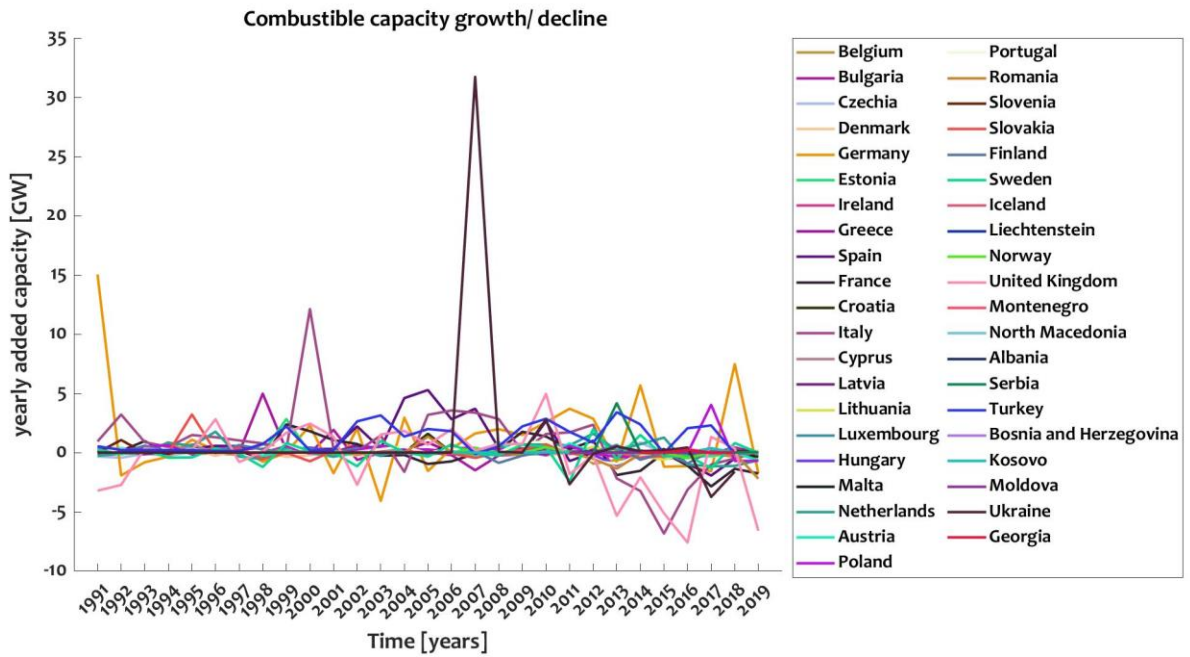


Figure A 3: Combustible capacity growth/decline.

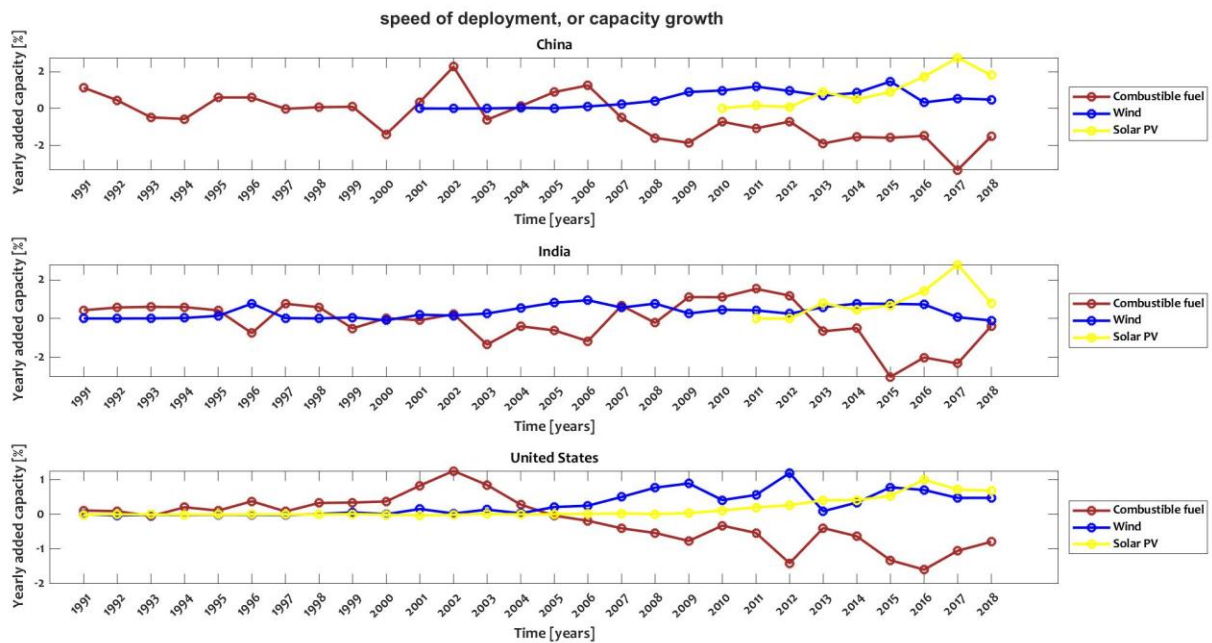


Figure A 4: China, India, the US capacity growth as percent/ system change.

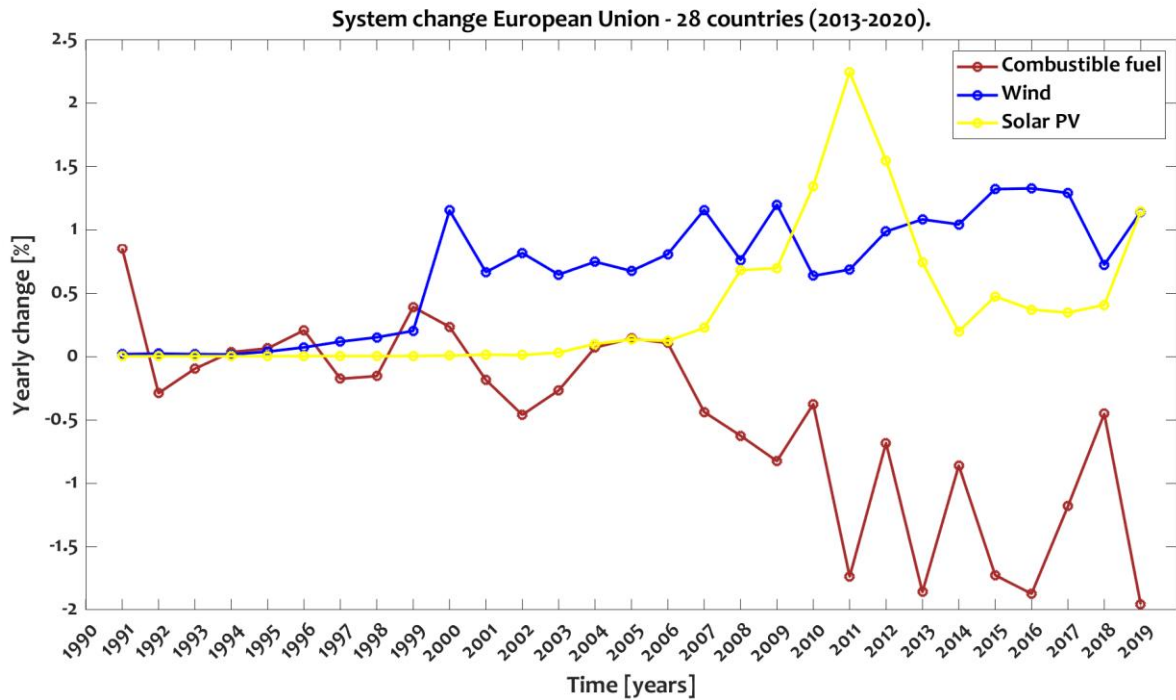


Figure A 5: System change EU 28.

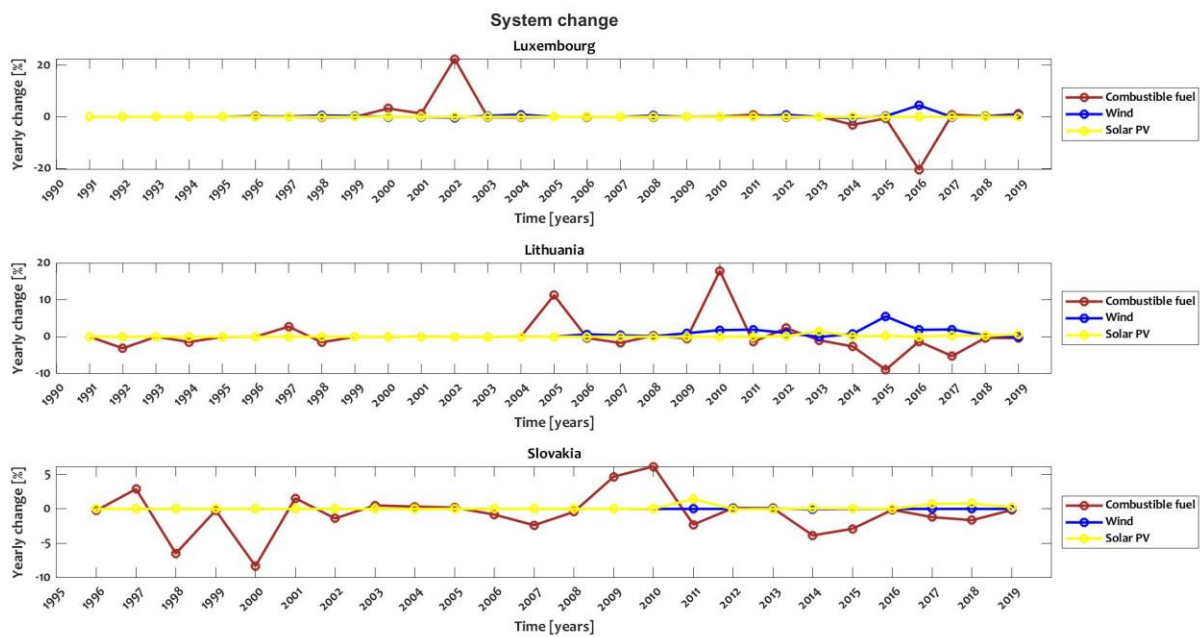


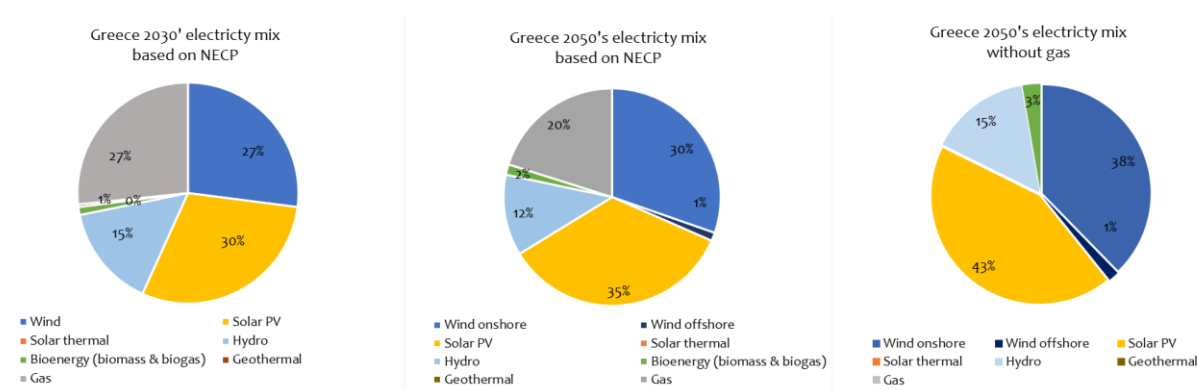
Figure A 6: Luxembourg, Lithuania and Slovakia system change: combustible fuel decline.

## Appendix 2 Policy preferences & dynamics

### *Policy strategies*

**Data analysis.** We analysed and used results from the SENTINEL Deliverable 7.1 (V. Stavrakas et al., 2021) and MUSTEC Deliverable 7.3 (Lilliestam et al., 2019). The researchers within the two projects have reviewed policy documents from different organisations. In addition, we analysed further policy documents, such as NECPs and Climate Action plans. Furthermore, we analysed the report from PAC project (Climate Action Network Europe and European Environmental Bureau, 2020) to identify the minority storyline for a Paris compatible pathways towards climate neutrality. Here, we present results for the three SENTINEL case studies.

**Limitations.** Data may be lacking because the government has simply not formulated a specific position, or the information is vague (decrease or increase compared to “today”). We see this as an indication that the specific topic is not highly relevant to that government, and thus, it is acceptable that the models quantify that data point.



**Figure A 7:** Share of installed electricity capacity in Greece, assumed based on NECP and Long-term strategy 2050 targets in GW

### *Setback distances and densities*

**Data analysis.** This data describes the currently valid distance rules for new onshore wind power production in countries across Europe, as well the density restrictions onshore wind expansion in Greece. These are an indication of the current acceptance of wind power, with longer distances indicating higher wind power skepticism and hence suggesting that opposition is higher.

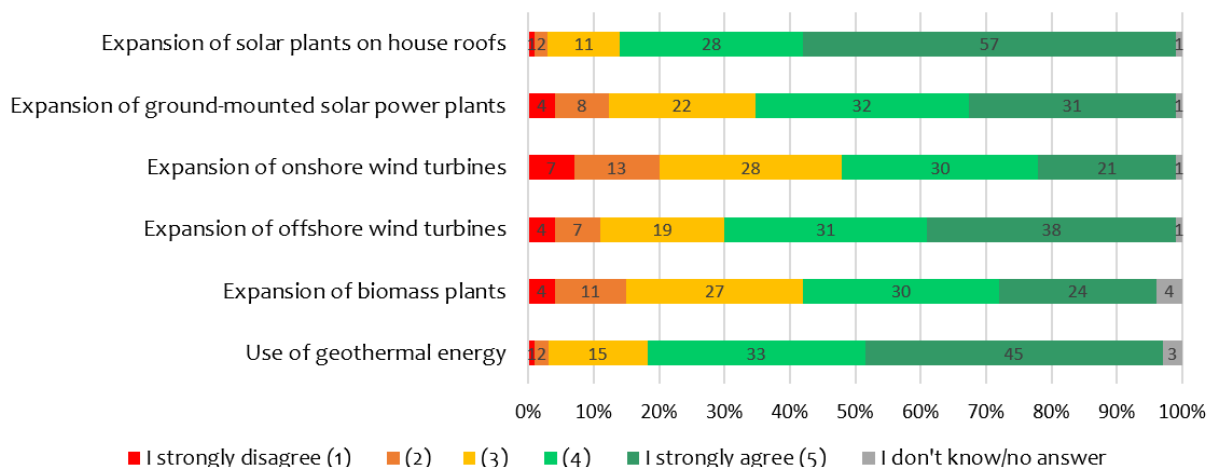
The main data source is the report “Wind potentials for EU and neighbouring countries” by JRC (Dalla-Longa et al., 2018). For some countries, we have referred to other more updated sources.

**Limitations.** Standards for minimum distances vary between countries and even regions, and are subject to fast and sometimes frequent policy changes.

## Appendix 3 People's attitudes towards renewable energy

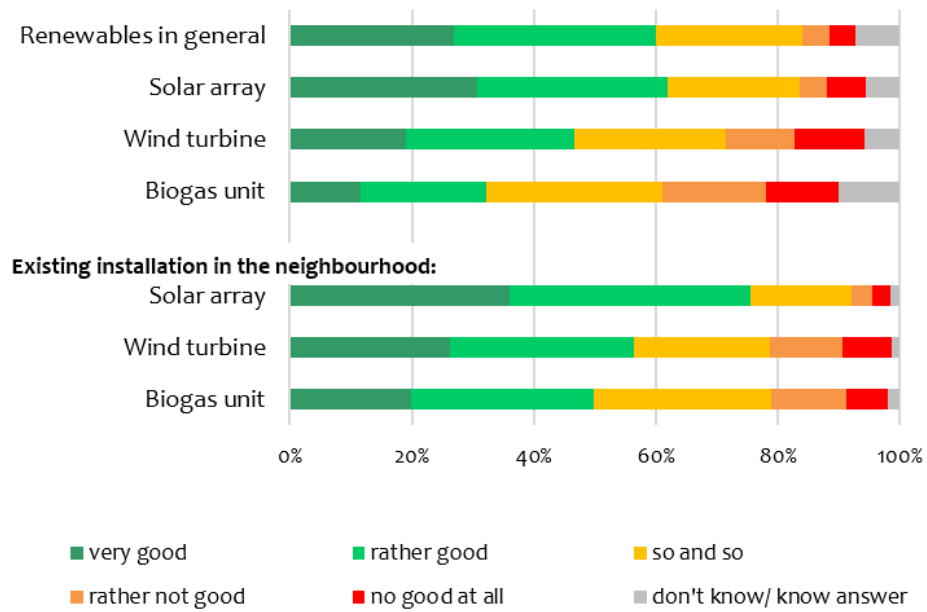
**Data availability.** Generally, there is a lack of data considering social acceptance of the energy transition across Europe. Studies often consider only a specific study region, or specific renewable energy sources. Here, we rely on data from the German Social Sustainability Barometer and the Agency for Renewable Energy (Agentur für Erneuerbare Energien).

**Data analysis.** We analysed the survey data from the German Social Sustainability Barometer for the years 2017-2019. Based on the agreement with the expansion/ use of different renewable energy technologies, we calculated a trend of the support over the three year. We used this trend agreements to define an electricity mix, or so called "electricity basket" based on the support. Furthermore, we analysed a survey data set by the Agentur für Erneuerbare Energie, for which YouGov conducted a survey on the opinions for renewables in people's backyards. We analysed to what degree people would (dis-)like renewable energy technologies in their neighbourhood.



**Figure A 8:** Personal stance for the expansion/ use of certain technologies, survey from 2019, n = 6,117 households, Germany. Data source: Wolf (2020).

### People's opinion for renewable energy in their backyard



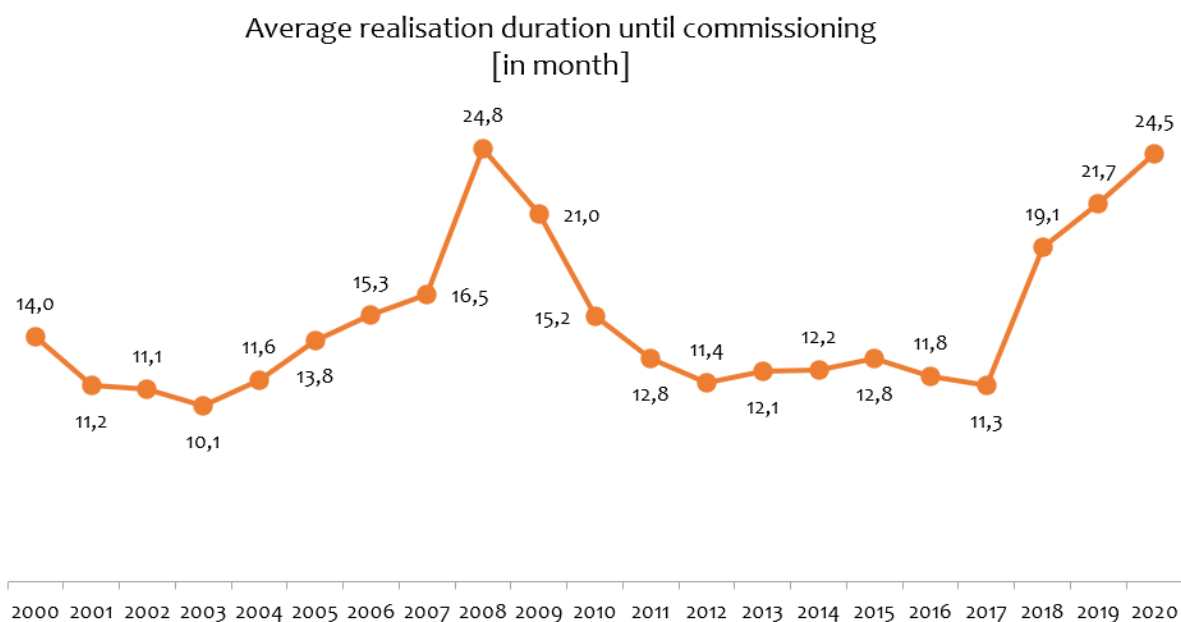
**Figure A 9:** People’s opinions about renewable energy in their backyard, survey 2020, n = 1051, Germany. Data source: YouGov conducted for Agentur für Erneuerbare Energien.

## Appendix 4 Barriers to infrastructure developments

**Data availability.** ENTSO-E provides very good data on the status quo of grid development projects. Data from WindEurope and SolarPower Europe have been requested for the status-quo of wind power and solar power projects on Member State level but data were not made available for non-Members. We analysed data from the Fachagentur Windenergie an Land for the development of wind energy projects in Germany.

**Data analysis.** For the assessment of the wind energy development in Germany, we analysed data by the Fachagentur Windenergie an Land (Quentin, 2019). Furthermore, we have analysed the ENTSO-E TYNDP 2020 data to identify grid developments, delays, and cancellations (transmission + storage).

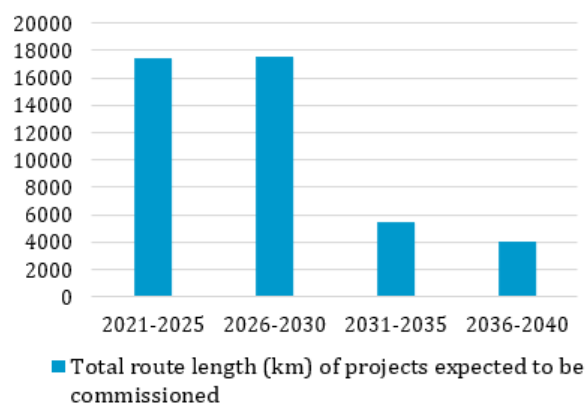
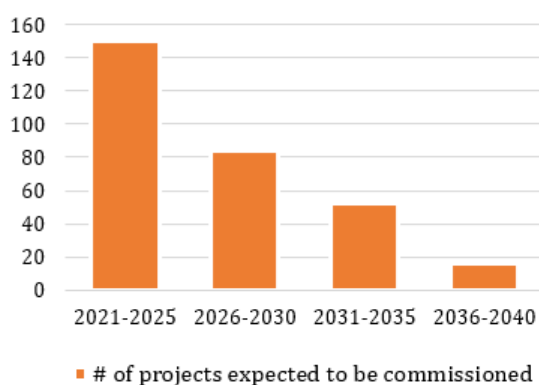
**Limitations.** Project delays grid development: there are not data on duration of delays and reasons for each project delay. But ACER reports in its 2020 report that “The most frequently reported reason for delays (i.e. for 11 out of 27 delayed PCIs, 40%) is related to permitting (including environmental problem, public opposition, required technical changes, additional assessments or rejection of permit by the authority)” (ACER, 2020).



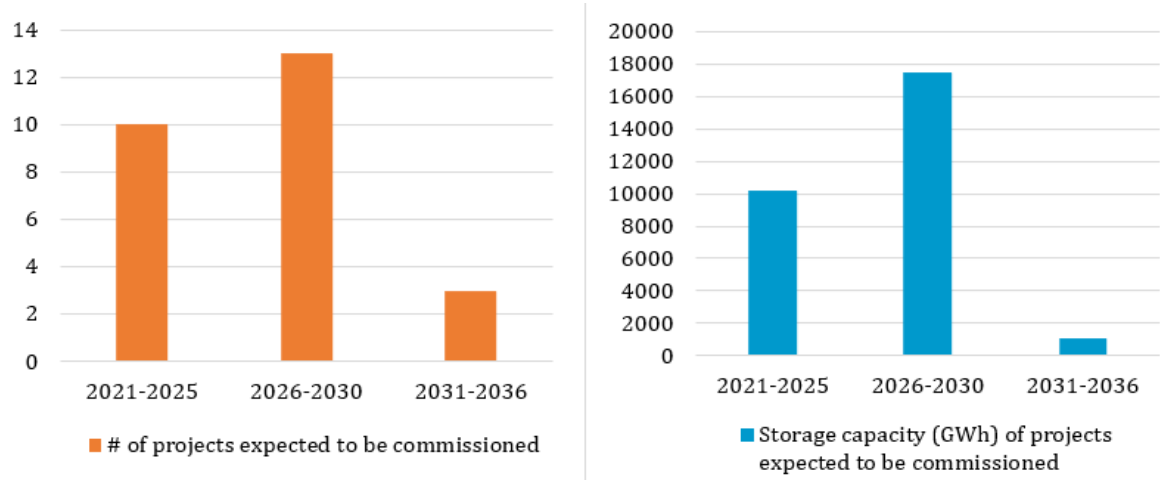
**Figure A 10:** Average realisation time for wind energy projects in Germany.

**Table A 1:** Litigation of approved wind power plants on land. Source: Fachagentur Windenergie an Land, Status: May, 2019 (Quentin, 2019)

Federal state of Germany	Wind power plants in litigation	Capacity [MW]	Share [%]	Total wind power plants	Capacity [MW]	Share in litigation (of wind power plans) [%]	Share in litigation (of MW) [%]
Baden-Württemberg	19	64.8	6	70	234.8	27	<b>28</b>
Bayern	26	75.6	7	59	182.0	44	<b>42</b>
Brandenburg	28	77,9	7	213	681.4	13	<b>11</b>
Hessen	26	75.1	7	61	190.4	43	<b>39</b>
Mecklenburg-Vorpommern	15	47.5	4	111	335.3	14	<b>14</b>
Niedersachsen	45	139.1	13	225	746.6	20	<b>19</b>
Nordrhein-Westfalen	48	164.3	15	227	758.0	21	<b>22</b>
Rheinland-Pfalz	18	55.9	5	100	305.3	18	<b>18</b>
Saarland	3	9.0	1	14	37.3	21	<b>24</b>
<b>Total</b>	<b>228</b>	<b>709.0</b>		<b>1,080</b>	<b>3,471.0</b>	<b>21</b>	<b>20</b>



**Figure A 11:** Expected grid developments in numbers and lengths, according to TYNDP (ENTSO-E, 2021a).



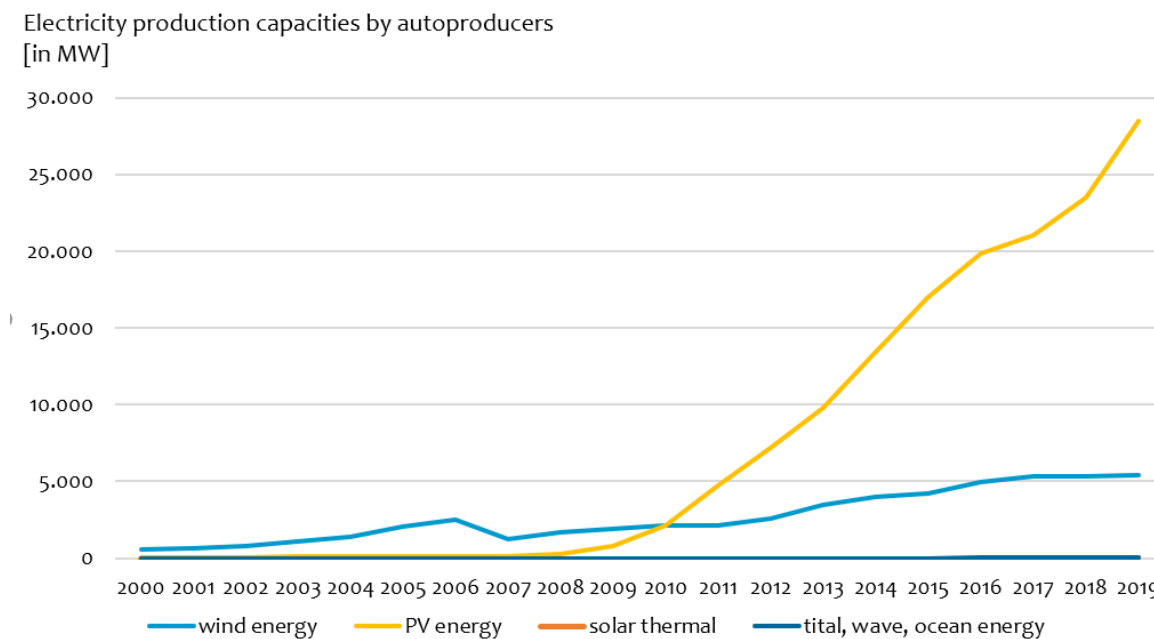
**Figure A 12:** Expected grid developments for storage in numbers and capacity, according to TYNDP (ENTSO-E, 2021a).

## Appendix 5 Citizen energy

**Data availability.** We analysed the Eurostat dataset on the *Electricity production capacity by main fuel groups and operator*. Further sources indicated some numbers of citizens energy and citizen energy companies, but not datasets were openly available.

**Description of data analysis.** To calculate the electricity capacity of autoproducers, we used the Eurostat data, and calculated capacity as well as percentages of the total capacity for renewables (wind, PV, solar thermal, wave/tidal/ocean energy). We extrapolated the data for future autoproducer capacity by taking the average increase over the last ten years.

**Limitations.** The data for autoproducers are not reported by all EU countries. For example, Germany and Denmark do not provide the data or not over the whole time-period. Thus, we expect the actual percentage of autoproducers to be higher.



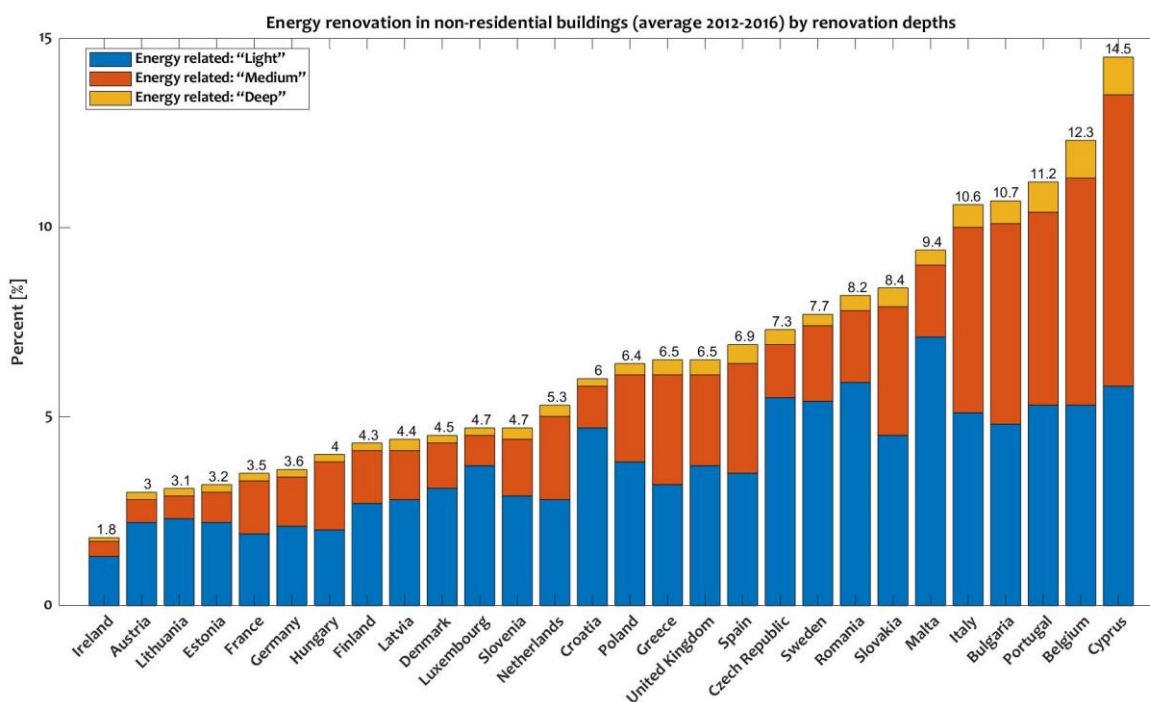
**Figure A 13:** Electricity production capacity by autoproducers in the EU 28. Note: the graph for solar thermal lies behind the graph for tidal, wave and ocean energy. Data source: Eurostat, 2021.

## Appendix 6 Energy demand

**Data availability:** Regarding the *building renovation rates*, the EC states that “renovation monitoring is poor and for the moment there is no data to assess if the 3% has been reached.”<sup>48</sup> We used the latest dataset of an EC-study by Ipsos Belgium and Navigant (2019) that contains information on the energy renovation in residential buildings and non-residential buildings for different renovation levels. Furthermore, we used the Eurostat data on Size of housing to assess the average number of rooms per person for houses and flats.

**Data analysis:**

- 1) We visualised the building renovation rates and sorted the data to find the countries with the highest renovation rates.
- 2) We calculated the change in the last five years (2015-2016-2017-2018-2019) in the number of rooms per person in houses and flats. We calculated the average number of rooms per person and presumed a constant development, equal to the average value, in the number of rooms per person over the following years. It is also possible to assume an increase or decrease instead of the average. We highlighted the countries with the largest and smallest number of rooms per person.



**Figure A 14:** Energy renovation in non-residential buildings, sorted by overall renovation rate. Data source: Directorate-General for Energy (European Commission) et al., 2019.

<sup>48</sup> [https://ec.europa.eu/energy/content/setting-3-target-public-building-renovation\\_en](https://ec.europa.eu/energy/content/setting-3-target-public-building-renovation_en)

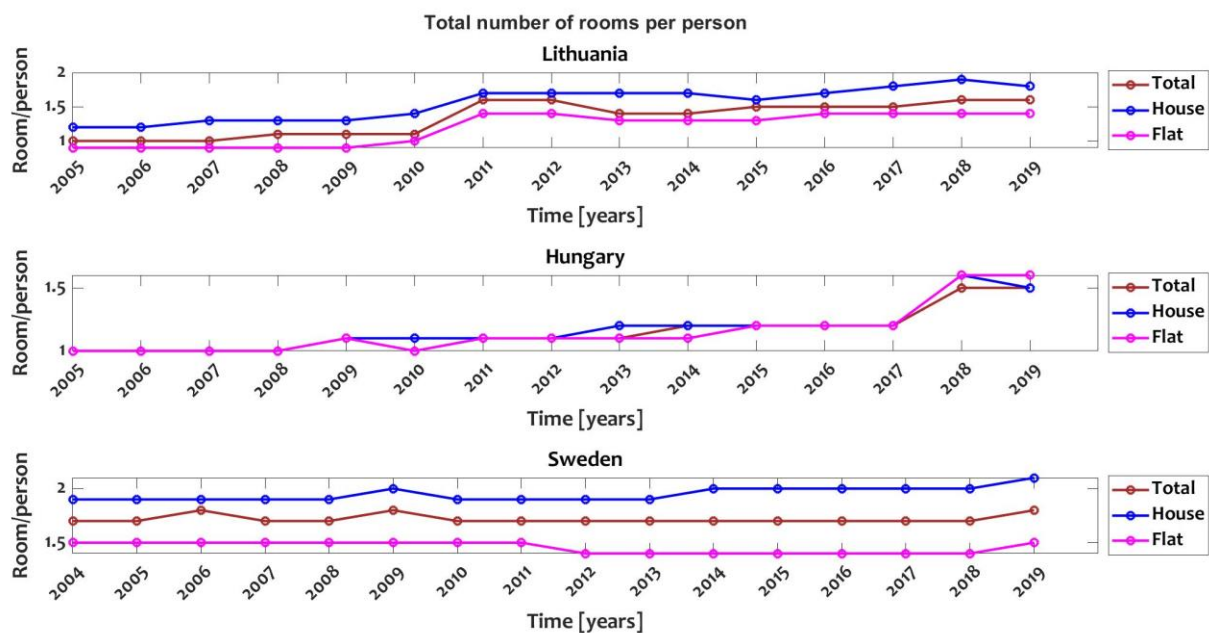


Figure A 15: Lithuania, Hungary, Sweden total number of rooms per person. Data sources: Eurostat, 2019, 2020.

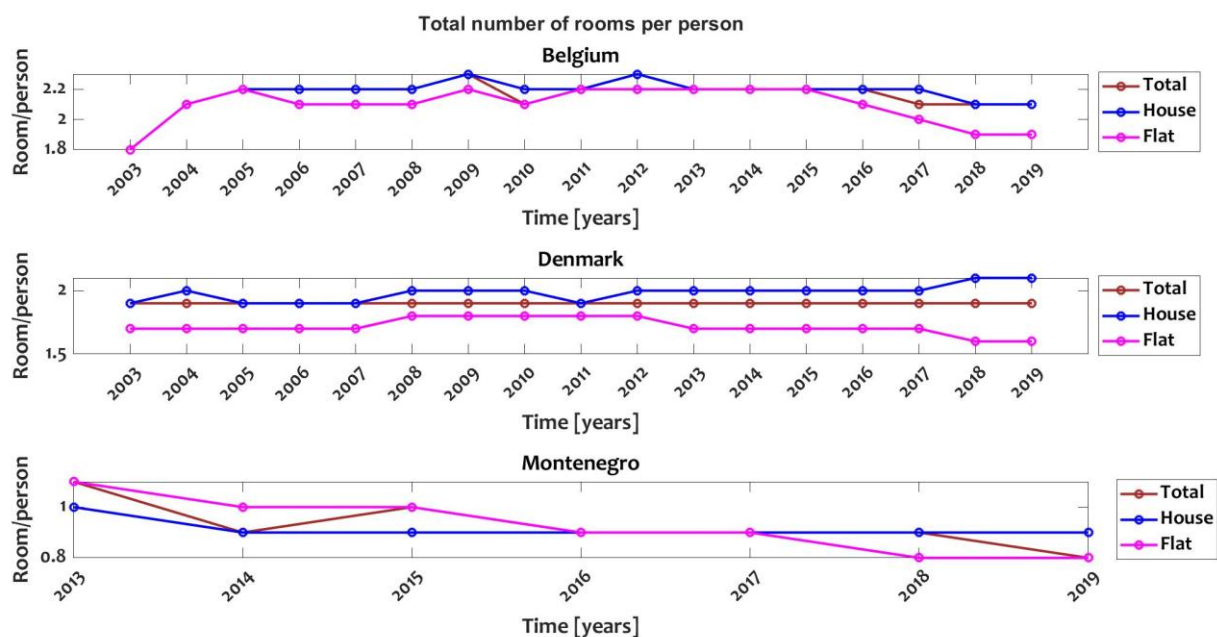


Figure A 16: Belgium, Denmark, Montenegro total number of rooms per person. Data sources: Eurostat, 2019, 2020.