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

June 2021
Version 1

SENTINEL

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IASS
POTSDAM

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Abbreviations, acronyms, and units

CAN	Climate Action Network
CO_2	Carbon Dioxide
COVID-19	Coronavirus Disease 2019
EE	Energy Efficiency
EEB	European Environmental Bureau
EU	European Union
ETS	Emission Trading System
GHG	Greenhouse Gas
GW	Gigawatt
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
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 this report, we (i) develop qualitative social storylines of the energy transition that specifically consider the social developments and dynamics of the energy transition; and (ii) provide quantifications for six thematic elements of the social storylines, in formats allowing these data to be directly used in energy models. We develop QTDIAN based on the needs of both modellers and users of the models, which we identified in SENTINEL WP1 and WP7. We develop the social storylines based on transition theory and on empirical observations of actual drivers and barriers. The output of QTIDIAN 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 two 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 common 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.

In upcoming SENTINEL work, we will apply the storylines and data in the different models and additional deliverables in SENTINEL to generate new insights based on SENTINEL model improvements in combination with the QTDIAN storylines and datasets. Based on feedback from the modelling exercises, QTDIAN may be revised and published in an updated report to improve its usefulness for the continued development and application of the SENTINEL model suite.

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. Considering that this transformation needs to be socially, economically and politically accepted, it is of utmost importance to facilitate it in a way that enables a 'just transition', leaving no one behind (European Commission, 2020).

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; Reusswig 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., n.d.). 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 and quantify social, technical, and political aspects of the energy transition to be integrated in energy models.

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. Our aim is 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. 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. Finally, in **section 5**, 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** summarises the potentials for the integration of social aspects.

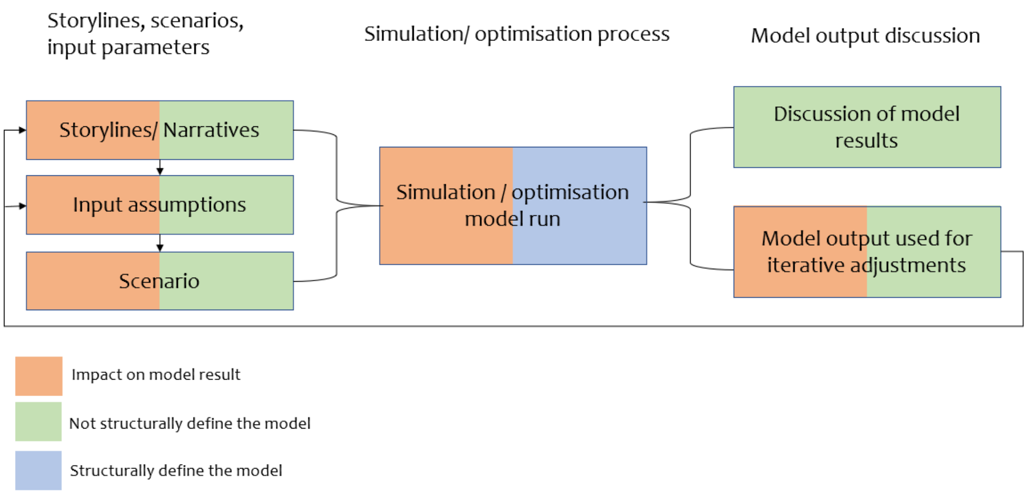

Figure 1: Potentials of integrating social aspects into models, own figure based on insights from Hirt et al., 2020; Trutnevyte et al., 2019; Turnheim et al., 2015.

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**).

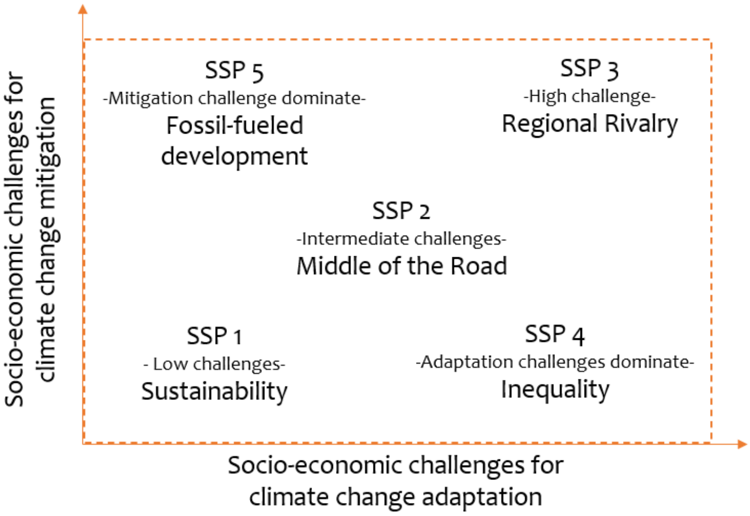

Figure 2: Five shared socioeconomic pathways (SSPs) representing different combinations of challenges to mitigation and to adaptation, own figure based on (O'Neill et al., 2017).

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.

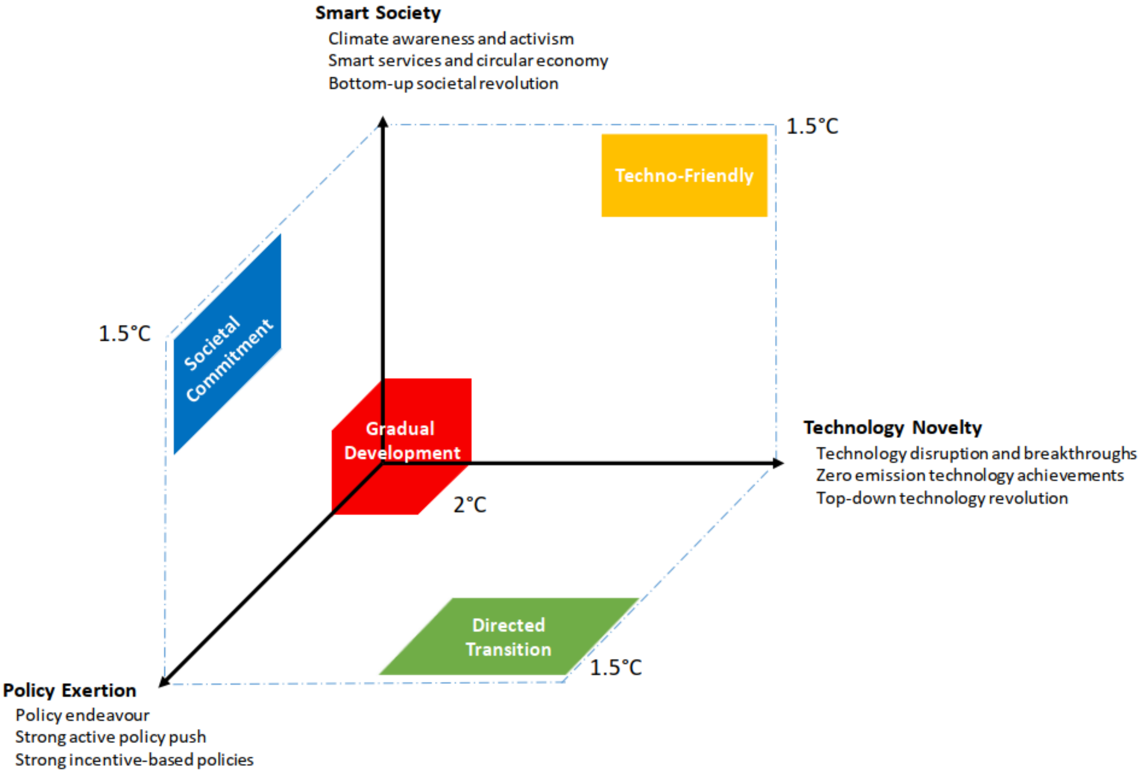

Figure 3: openENTRANCE storylines typology. Source: Auer et al. (2019), CC-BY-4.0.

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 in 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**). 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-let),
- Central co-ordination (government-led), and
- Thousand flowers (civil society-led).

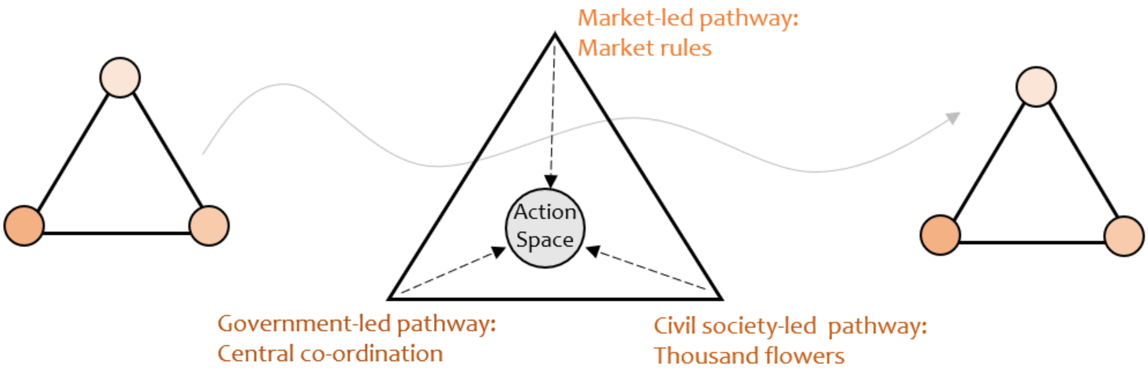

Figure 5: Core transition pathways to a UK low carbon electricity system, own figure after Foxon (2013).

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**. 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 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.).

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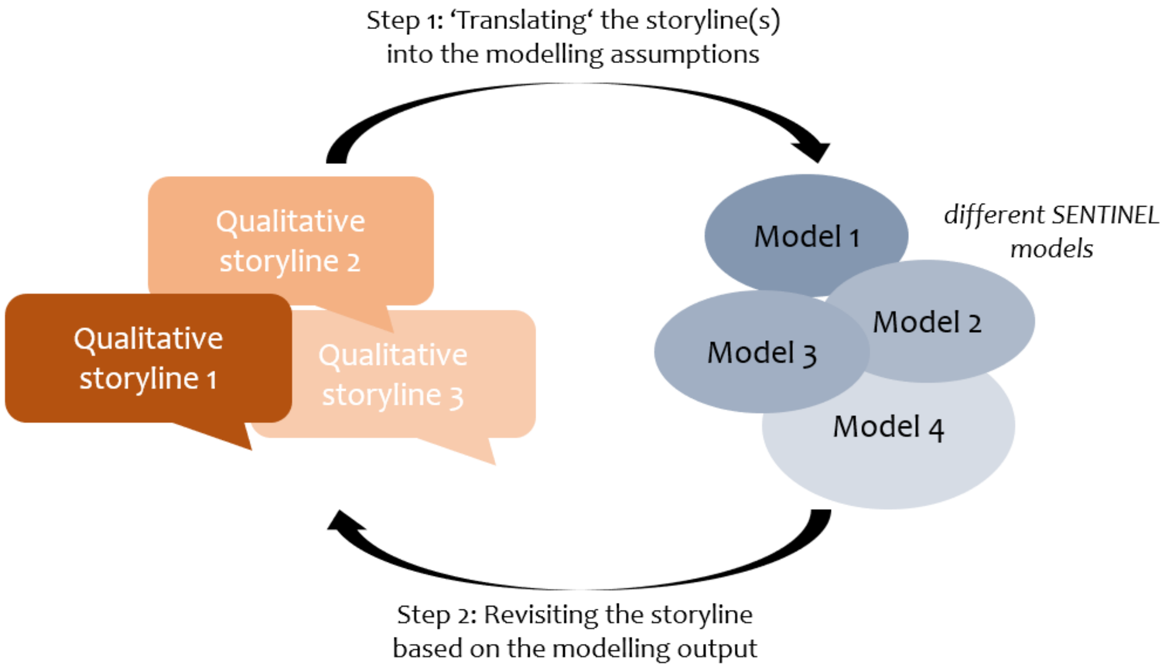

Figure 6: The iterative process of linking storylines with multiple cross-scale quantitative models, own figure after Trutnevyte et al. (2014).

3 User needs for the development of QTDIAN

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[1]. 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** provides an overview how user needs have influenced the definition and implementation of QTDIAN. Users will be further engaged in the context of WP7 of the project to receive feedback if the different needs have been met and what the different modelling results imply.

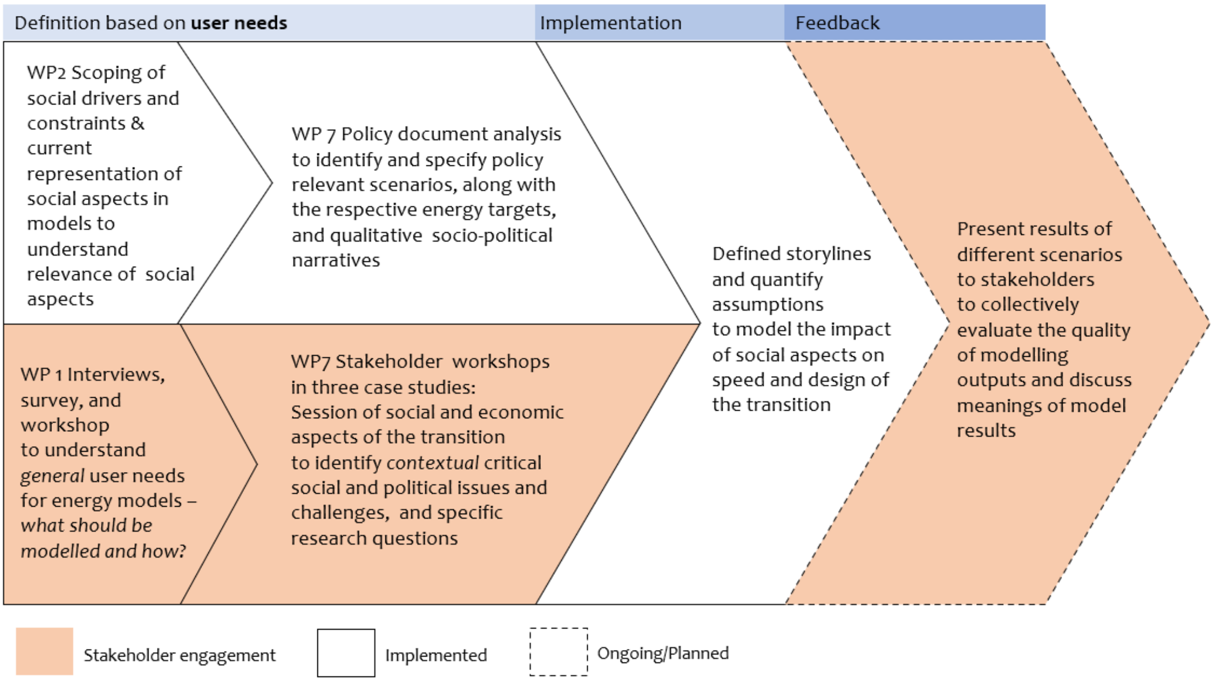

Figure 7: Consideration of user needs for the development of QTDIAN. This Deliverable reports on the implementation stage.

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[1] https://sentinel.energy/model-catalog/

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
Local opposition towards energy infrastructures	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?
Social acceptance/ preferences towards renewable energy technologies	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?
Citizen and community ownership	Social storylines include ownership and (de)centralised tech system design; quantifications of autoproducers and citizen energy companies	How does ownership affect the system design?
Policy preferences and dynamics	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?
Social technological scaling / scaling of the economy	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 other SENTINEL models and, naturally, also other models outside the projects. 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.

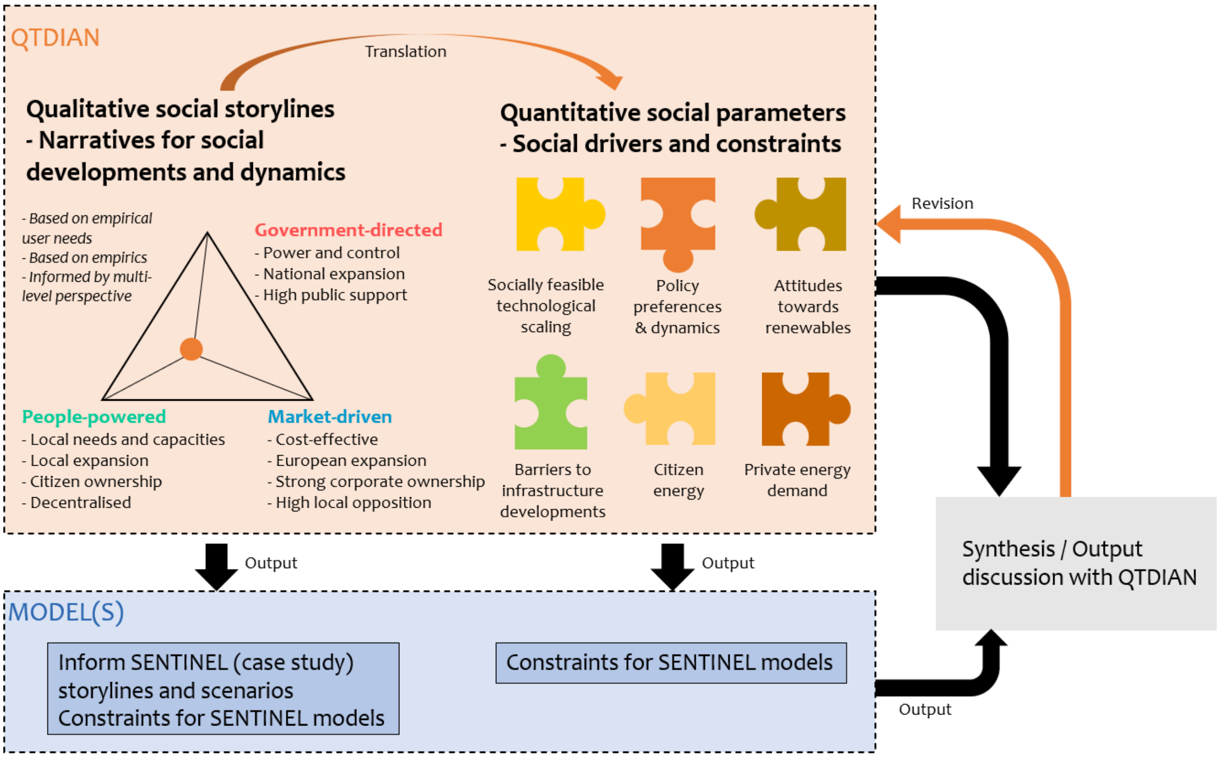

Figure 8: Overview of the QTDIAN modelling toolbox.

The QTDIAN data as described below is to be understood as the first round of an iterative process. The data are available at ZENODO (Süsser et al., 2021b). Following the completion of this report, the QTDIAN data will be used in different SENTINEL suite models. We expect that this process will show that some datasets are useful the way they are, but also that some may need revision. If this happens, we will update that dataset and publish it in a further version of QTDIAN.

4.1 QTDIAN social storylines of the European energy transition

The first element of QTDIAN are *social storylines* – narratives describing societal developments, and interactions and interdependencies between actors, technologies, and policy interventions in the European energy transition.

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

To develop the storylines, we engaged with stakeholders in the framework of WP1 and WP7, 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**). 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.

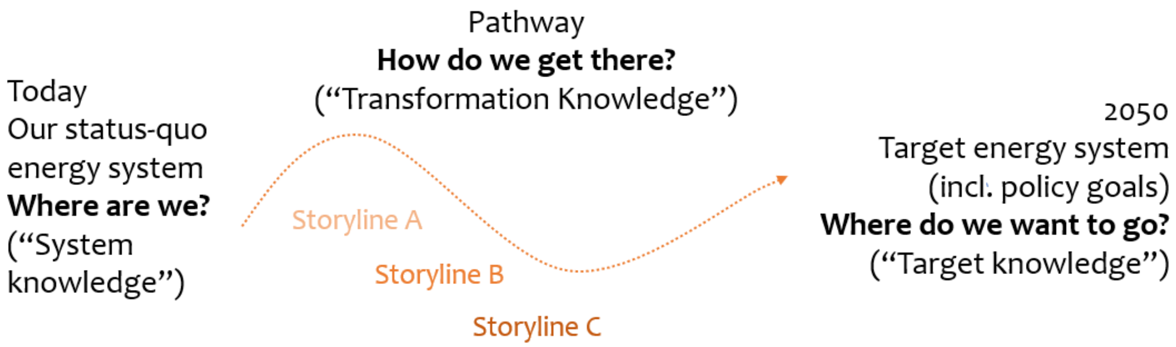

Figure 9: Three types of knowledge structure the storylines; based on Stavrakas et al. (2021) and Network for Transdisciplinarity Research (2021).

To systematise the narratives and describe types of narratives, rather than each stakeholder's individual story, we draw on the framework of governance logics by Foxon (2013) and Foxon et al. (2010). We observe that many of the factors that drive and constrain the energy transition are not technical or economic, but rather concern how the transition should happen and how the final-state energy system should be designed: 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, **Figure 10**): 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).

The three QTDIAN social storylines of the energy transition are based on different 'logics' dominating the transition: a people-powered, a government-directed, and a market-driven transition storyline. The three QTDIAN storylines are 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). 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 **Figure 10**, QTDIAN 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.

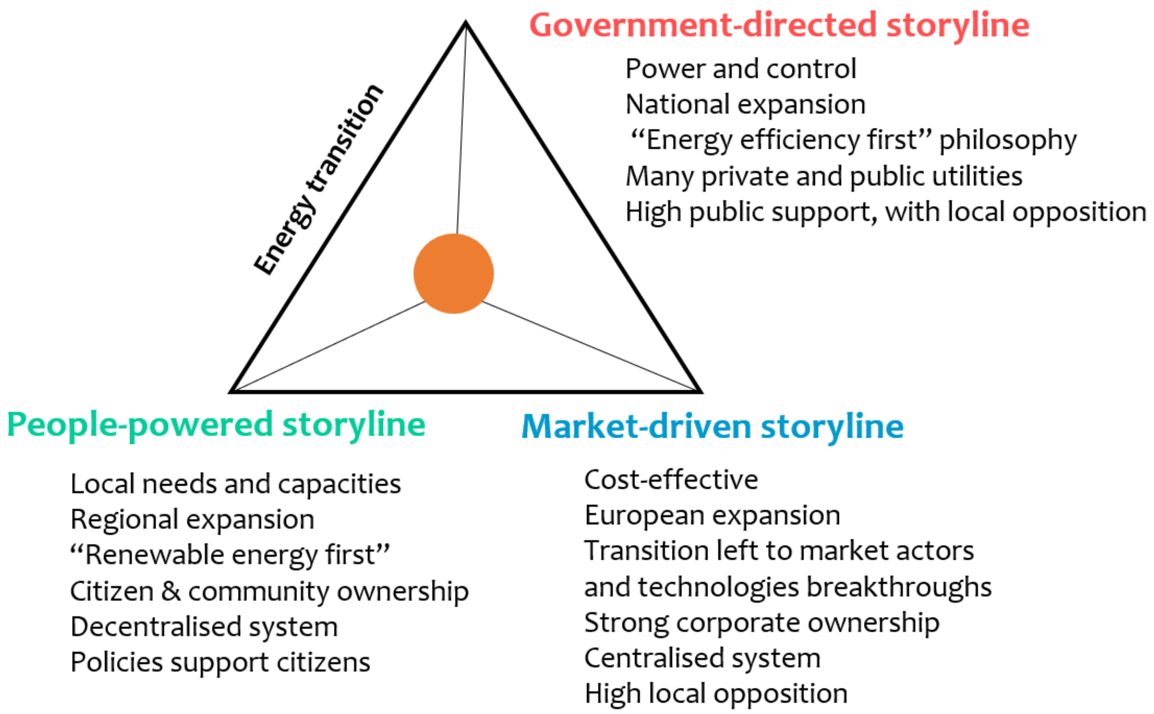

Figure 10: The energy transition logics and their use for the QTDIAN social storylines; adapted from Foxon (2013).

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)[2]. 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)[3]. The EU's energy transition framework for the post-2020 period is defined in the policy package *Clean energy for all Europeans*[4] – and that name also sets the European long-

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

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

[4] ttps://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en

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 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 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.

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)[5]. 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

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[5] https://ec.europa.eu/energy/topics/energy-strategy/energy-union_en

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.

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 fa 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.

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 increases 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.

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 in 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
Where do we want to go?			
Energy system 2050	climate-neutral, mainly renewable-energy-based		
Resulting social system design:			
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
Households' electricity consumption (except electric heat)	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)

Storyline features/ variables	**People-powered**	**Government-directed**	**Market-driven**
Resulting tech system design:			
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
Mobility	Shared solutions are common; fewer, decarbonised cars	Transport systems change only moderately; expansion public transport; the number of cars on the street remains largely constant	Little emphasis on public and communal solutions; public transport is hardly expanded, and personal mobility remains car-based
How do we get there? Drivers/ barriers			
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 and living space.

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 are available at ZENODO (Süsser et al., 2021b).

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 [MAX (GW/year$_t$) / (GW/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
Maximum change rate: Installed combustible capacities	Capacity growth [GW/year] Maximum change rate over 5 years [MAX (GW/year$_t$) / (GW/year$_{t-5}$)] System change per year [% of total system capacity added/year]	EU 28+ World countries and areas World countries and areas	1990-2019 1990-2019 2000-2019	Eurostat, 2019 UN, 2021 IRENA, 2021	Open Open Open
Maximum change rate: Installed wind power capacity (onshore and offshore)	Capacity growth [GW/year] Maximum change rate over 5 years [MAX (GW/year$_t$) / (GW/year$_{t-5}$)] System change per year [% of total system capacity added OR removed/year]	EU 28 + World countries and areas World countries and areas	1990-2019 1990-2019 2000-2019	Eurostat, 2019 UN, 2021 IRENA, 2021	Open Open Open
Maximum change rate: Installed solar PV capacity	Capacity growth [GW/year] Maximum change rate over 5 years [MAX (GW/year$_t$) / (GW/year$_{t-5}$)]	EU 28+ World countries and areas	1990-2019 1990-2019 2000-2019	Eurostat, 2019 UN, 2021 IRENA, 2021	Open Open Open

	System change per year [% of total system capacity added/year]	World countries and areas			

(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[6], 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

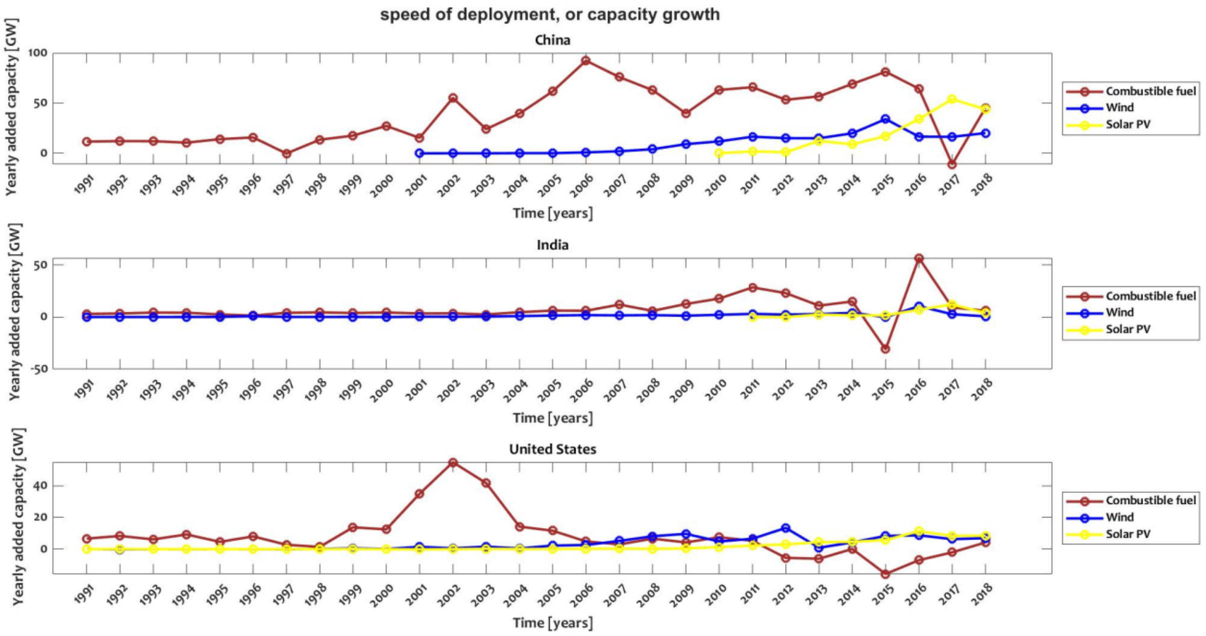

Figure 11: China, India, the US capacity growth. Data source: UN, 2021.

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

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[6] 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.

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

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 t build-up solar capacity; the highest solar capacity addition was in 2017 with 54.11 GW. China started in 2001 built-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 built-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.

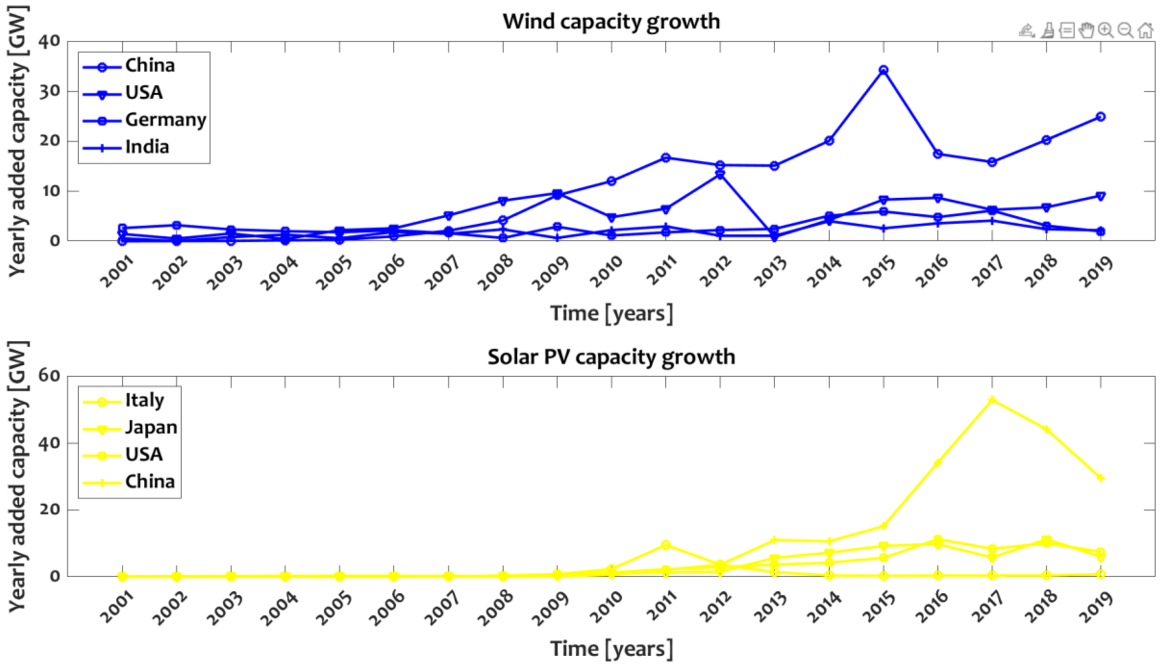

Figure 12: Capacity growth for wind and solar PV, fastest countries. Data source: IRENA, 2021.

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.

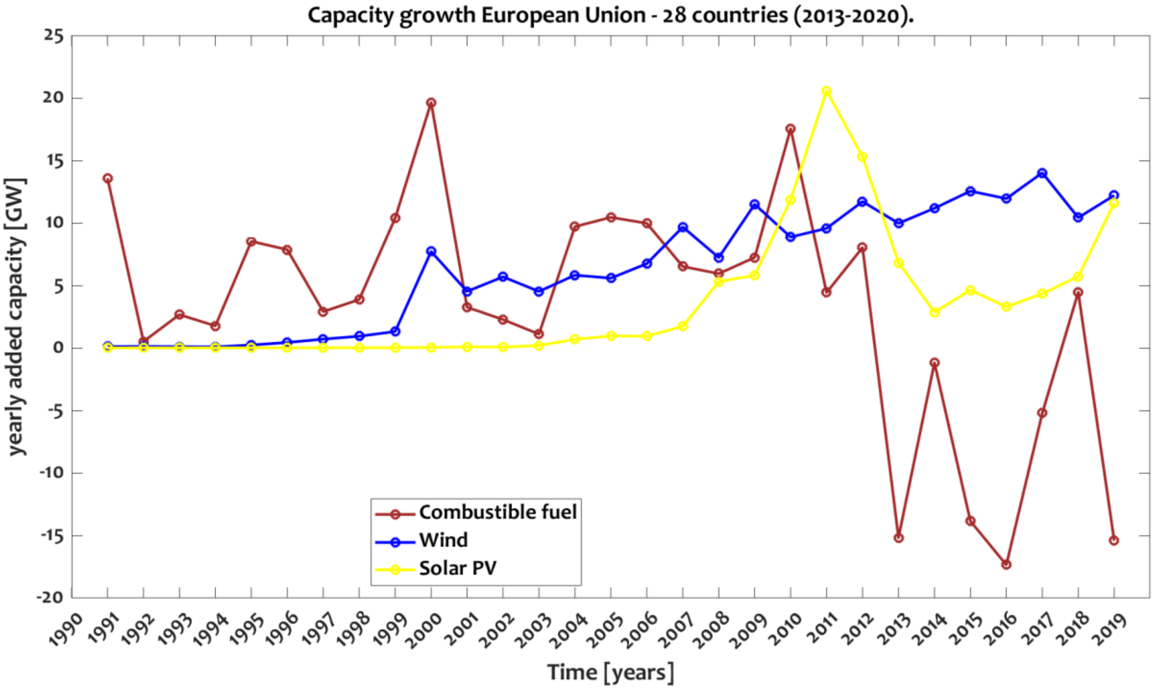

Figure 13: Capacity growth/decline EU 28.

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[7], 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 %

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[7] Only data for solar PV and wind are available.

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.

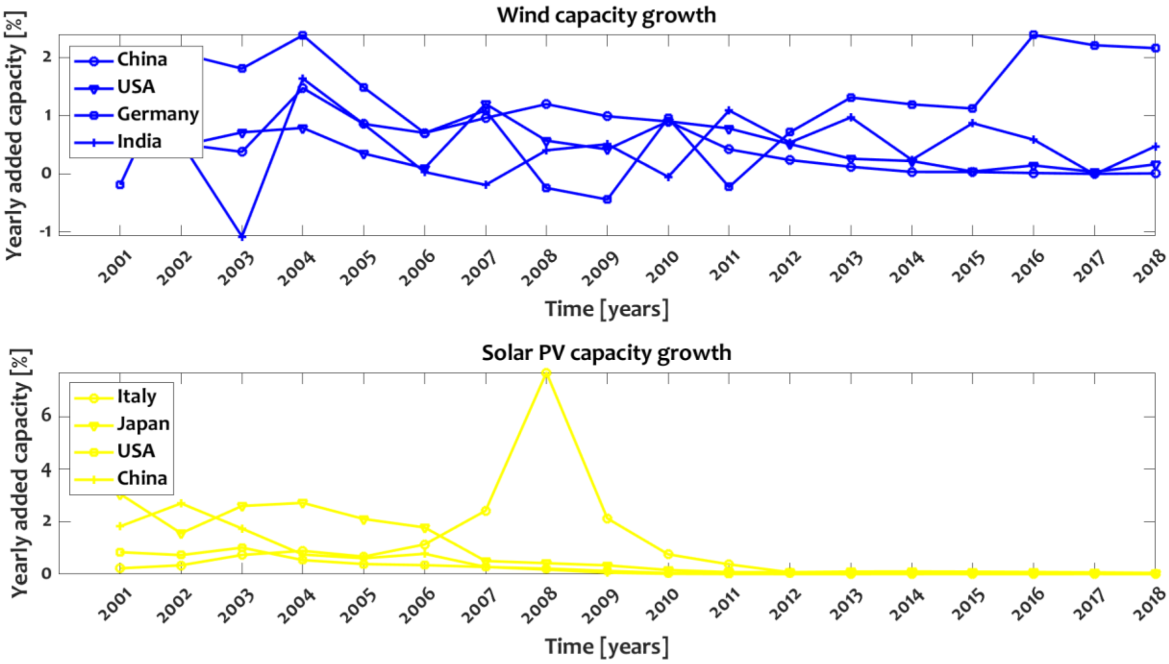

Figure 14: Capacity growth as percent, Wind and PV, fastest countries. Data source: UN and IRENA data.

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**).

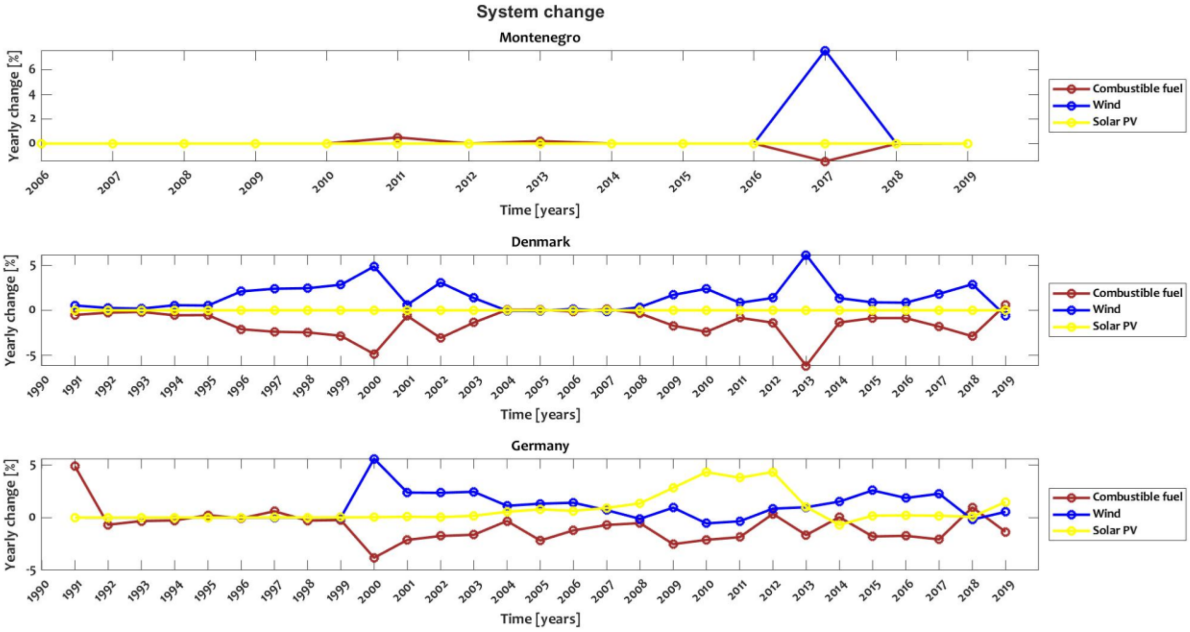

Figure 15: Montenegro, Denmark, and Germany system change.

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.

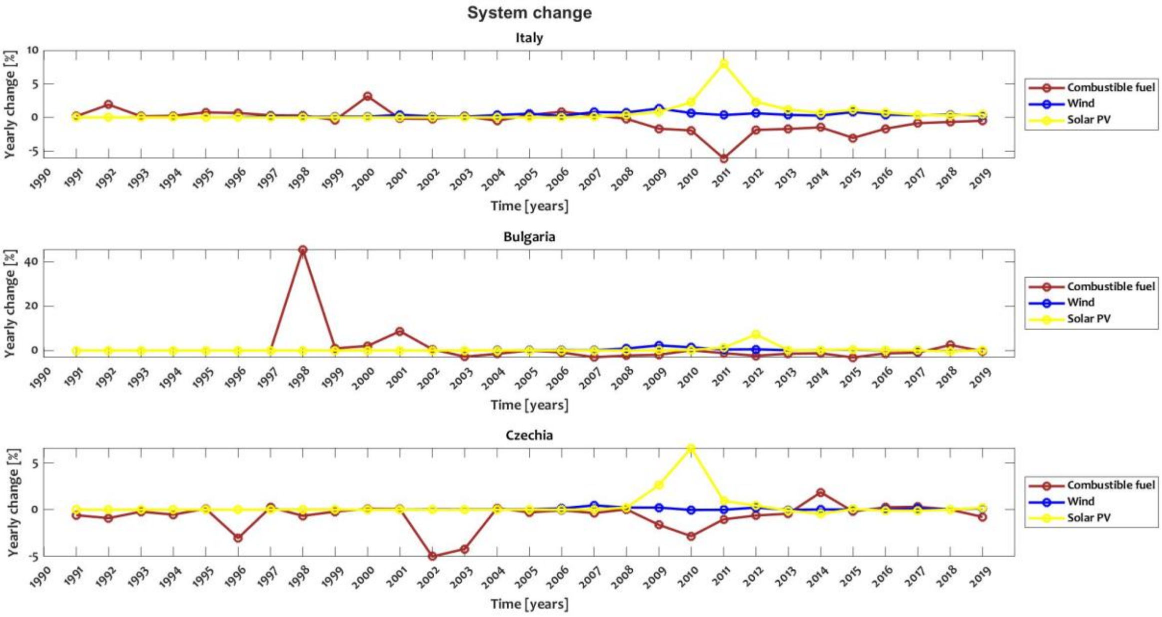

Figure 16: Bulgaria, Czechia, and Italy system change.

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.
  2) **Table 4** illustrates the available model input parameters.
  3) 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. **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 [%]	EU, Denmark, Norway, Greece

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[8]. 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)[9]) and market push policies (e.g., NER 300 programme[10]), 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; Stavrakas et al., 2021).

	2030	**2050**
Total GHG emission reduction target	>55% reduction (GHG-1990)[11]	100% / climate neutrality
ETS sector reduction targets; Non-ETS sectors emission reduction targets	ETS: 43% (GHG-2005), 2.2% per year; Non-ETS: 30% (GHG-2005)	100%
Renewable energy in gross final energy consumption	32%[12]	>2030 and >2040
Renewable energy in gross final consumption in transport	>14%	-60% (GHG-1990); 65% renewables
Energy efficiency improvements: Energy intensity;	32.5% (compared to projections of the expected energy use in 2030);	>2030 and > 2040

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

[9] https://ec.europa.eu/clima/policies/ets_en

[10] https://ec.europa.eu/clima/policies/innovation-fund/ner300_en

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

[12] https://ec.europa.eu/energy/topics/renewable-energy/renewable-energy-directive/overview_en

Translated energy consumption	final energy consumption of 956 Mtoe and/or primary energy consumption of 1,273 Mtoe in the EU 28 [13]	
Final energy consumption	-26% primary energy (2005); -20% final energy (2005); -0.8% final energy per year (baseline 2020)	-0.8% final energy per year (baseline 2020)
Heating demand		-90% (GHG-1990); Heating with electricity > today
Cross-border interconnection NTC	≥15% of yearly power production	
Residential building renovation	3% per year[14]	

(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 Comission, 2020).

Minority pathway

The minority pathway we have analysed is the Paris Agreement Compatible (PAC) energy scenario, developed in the framework of the PAC project[15]. 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).

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

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[13] https://ec.europa.eu/energy/topics/energy-efficiency/targets-directive-and-rules/eu-targets-energy-efficiency_en

[14] https://ec.europa.eu/energy/content/setting-3-target-public-building-renovation_en

[15] 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.

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.

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**
Total GHG emission reduction target	-70% (GHG-1990)	net-zero emissions
Non-ETS sectors emission reduction targets	Non-ETS: 39% (GHG-2005)	
Renewable energy in gross final energy consumption	55%	-
Renewable energy in gross final electricity consumption	>100%	>100%
Renewable energy in gross final consumption for heating and cooling	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	
Percentage in gross final consumption for transport	19%	
Lignite in electricity generation	Phased-out by 2030	
Share of renewable electricity consumption*	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)	
Energy demand (expected)	Increase of 1 Mtoe in primary energy consumption; 0,5 Mtoe in final energy consumption (between 2021 and 2030)	
Electric mobility	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
Total GHG emission reduction target	-39% (GHG-2005); electricity and heat production nearly emission free	carbon neutrality
Renewable energy in gross final energy consumption*	>51%	-
Renewable energy in gross final electricity consumption	53%	
Renewable energy in gross final consumption for heating and cooling	61%	
Percentage in gross final consumption for transport	45%	
Renewable energy in gross final consumption in transport	30%	
Lignite, peat and oil in electricity generation	Phase-out by 2029; Halfing use of peat by 2030; >50% reduction in domestic use of imported oil	
Final energy consumption	<290 TWh (corresponds to approximately 405 TWh of primary energy consumption)	
Residential building renovation	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
Total GHG emission reduction target	-	- 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
Non-ETS sectors emission reduction targets		Non-ETS: 63% (GHG-1990)	Non-ETS: 70% (GHG-1990) by 2040
Renewable energy in gross final energy consumption	50%		(indicative trajectory: 65%)
Renewable energy in gross final electricity consumption	-		100% by 2040
Share of renewable energy consumption*		5 GW increase of wind power, and 2 GW solar power are expected between 2017 and 2030	
Energy efficiency improvement: energy intensity		-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[16]	-
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	

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[16] https://www.euractiv.com/section/climate-environment/news/greece-confirms-last-coal-plant-will-be-shut-in-2025/

	consumption in 2030 compared to that in 2017)	
Targeted energy savings	leading to energy savings of 7.3 Mtoe (in the period of 2021– 2030)	-
Final energy consumption	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% Bionergy: 9.9% Renewables in form of heat pumps: 8.6% District heating: 0.7% Petroleum products and fossil fuels: 0.2%
Energy storage: installed capacities	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
Residential building renovation	600,000 houses; 1.28% annual renovation rate	856,000 houses, 1.24% annual renovation rate
Electric mobility	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 21**). 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 21**). Moreover, the CAN Europe and ZERO (2020) demand for more ambitious objectives for GHG reductions in the **transport sector**. According to the NECP, CO_2 emissions from the transport sector are 18.1 Mt CO_2 in 2020 and are expected to be 17.2 Mt CO_2 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
Albania	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
Austria		Dalla-Longa et al., 2018
- **Niederösterreich**	1,200 meters	
- **Oberösterreich**	800 meters	
- **Burgenland**	1,000 meters	
Steiermark	1,000 meters	
Belgium		Dalla-Longa et al., 2018
- **Flanders**	at least 3 times the rotor diameter	
- **Wallonia**	400m, or 4 times the total height of the wind turbine	
- **Brussel**	Not permitted at all	
Bosnia and Herzegovina	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
Bulgaria	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
Croatia	Legislation suggests 45db noise limit, minimum of existing installations 350m (Noise Act, national legislation); JRC recommends using 500 meters.	Dalla-Longa et al., 2018
Cyprus	Differences apply between locations. JRC recommendation: 850 meters	Dalla-Longa et al., 2018
Czech Republic	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
Denmark	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[17] Dalla-Longa et al., 2018
Estonia	1000-2000 meters; JRC recommendation: 1000 meters	Dalla-Longa et al., 2018
Finland	1000-2000 meters; JRC recommendation: 1000 meters	Dalla-Longa et al., 2018
France	500 meters residential areas, and 300 meters from nuclear installations	Dalla-Longa et al., 2018
Germany	Differences between Federal States: from case-to-case to 10 times tower height; JRC recommendation: 500 meters	Fachagentur Windenergie, 2021[18]

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[17] 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)

[18] https://www.fachagentur-windenergie.de/fileadmin/files/PlanungGenehmigung/FA_Wind_Abstandsempfehlungen_Laender.pdf

Greece	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
Hungary	1000-2000 meters; JRC recommendation: 1000 meters	OpenGov, 2021[19] Dalla-Longa et al., 2018
Iceland	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
Ireland	40 dB and 500 meters	Dalla-Longa et al., 2018
Italy	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
Kosovo	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
Latvia	40-45 dB during the night; JRC recommendation: 500 meters	Dalla-Longa et al., 2018
Lithuania	<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
Luxembourg	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
Malta	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
Montenegro	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
Netherlands	4 times hub height (~400 meters); JRC recommendation: 400 meters	Dalla-Longa et al., 2018
Norway	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
Poland	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
Portugal	Noise regulation ~ 400 meters	Dalla-Longa et al., 2018
Romania	500 meters	Dalla-Longa et al., 2018
Serbia	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
Slovakia	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
Slovenia	JRC recommendation: 500 meters	Dalla-Longa et al., 2018
Spain	500-1000 meters	Dalla-Longa et al., 2018
Sweden	1000 meters to urban areas and 500 meters to isolated houses	Dalla-Longa et al., 2018
Switzerland	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

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[19] http://www.opengov.gr/minenv/?p=10255

UK - **England** - **Wales** - **Scotland** - **Northern Ireland**	 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
Country	**Density restriction for onshore wind**	
Greece	*in wind priority regions of the mainland:* maximum permissible wind farms land coverage rate for a municipality area cannot exceed 8% of the municipality area; *high tourism areas:* maximum allowable land coverage rate from wind farms cannot exceed 4% of the municipality area; *wind suitable regions of the mainland* (i.e., the regions not included in wind priority regions): maximum permissible wind farms land coverage rate cannot exceed 5% of the municipality area	OpenGov, 2021[20] Dalla-Longa et al., 2018

(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)

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[20] http://www.opengov.gr/minenv/?p=10255

- **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** next page).

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.

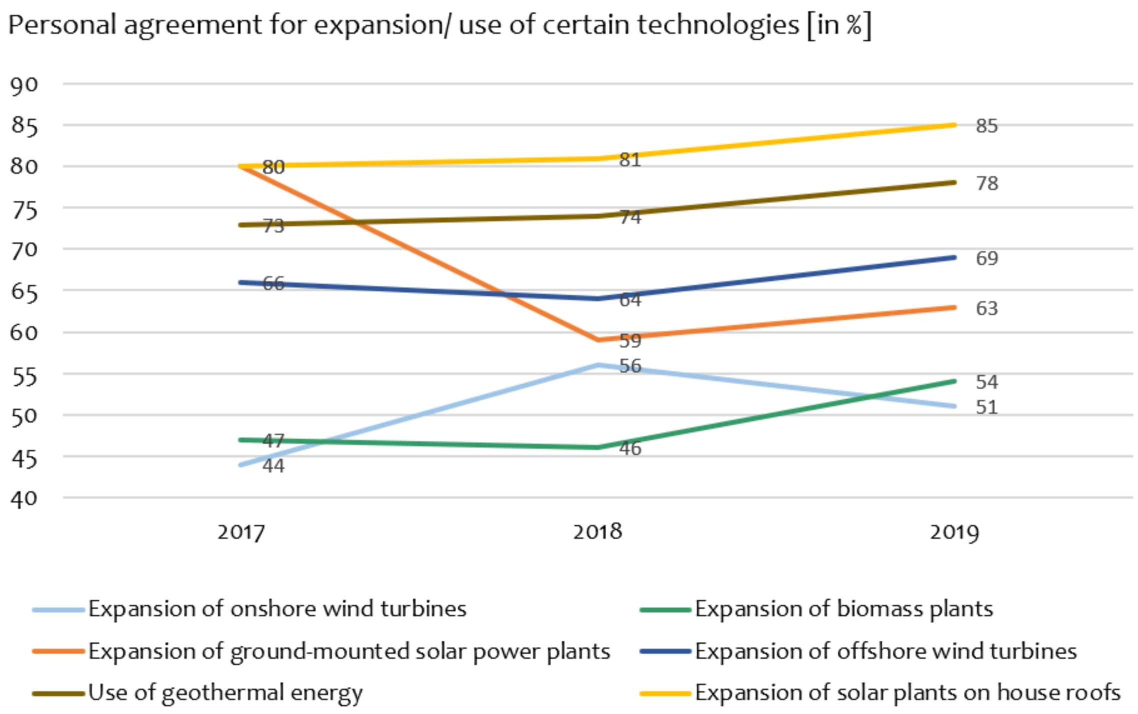

Figure 17: Personal agreement for the expansion/ use of certain technologies, respondents who answered 4 or 5 (strong agreement), surveys 2017-2019, Germany. Data source: Wolf (2020).

4.2.4 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
Onshore wind power development: Realisation duration, project litigation and duration of proceedings	Average realisation time from granting of the immission control permit to commissioning [months]	Germany	Fachagentur Windenergie and Land, Marktstammdatenregister	On request
	Percentage of projects with litigation [%], and average duration of proceedings in months	Germany	Fachagentur Windenergie an Land (Quentin, 2019)	On request
Grid development (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 Percentage of projects delayed [%] Delays in months	EU 28	ENTSO-E TYNDP 2020 Projects Sheets ACER list of projects of common interest (PCI)	Open

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 (TYNPD) 2020 (ENTSO-E, 2021), over 300 transmission projects are expected to be commissioned[21] 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.

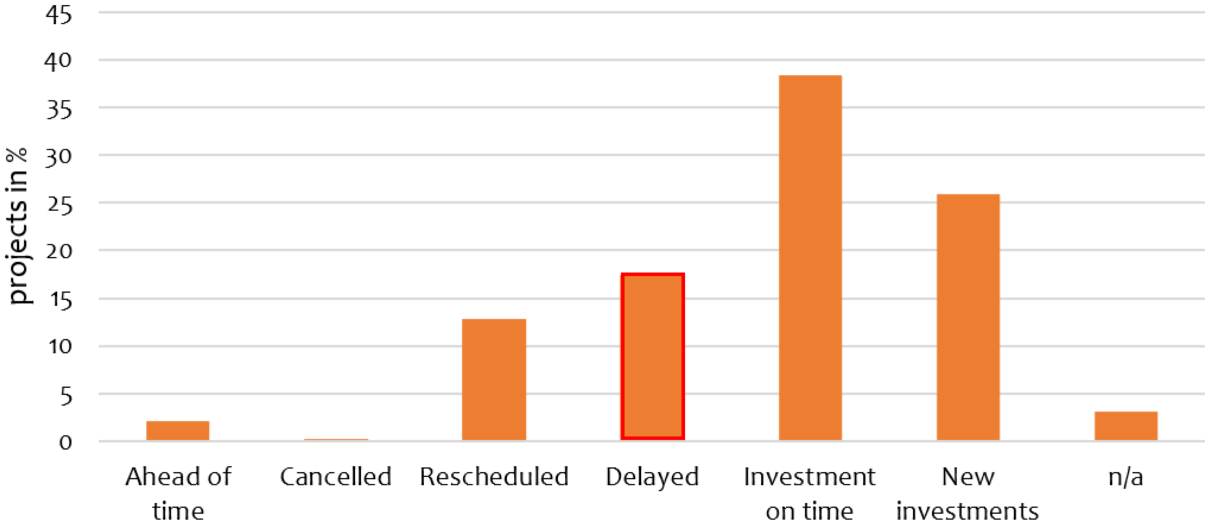

Figure 18: Progress of transmission investments since TYNDP 2018, n = 321 projects.

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 TYNPD 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.

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[21] based on the year of commissioning provided by project promoters

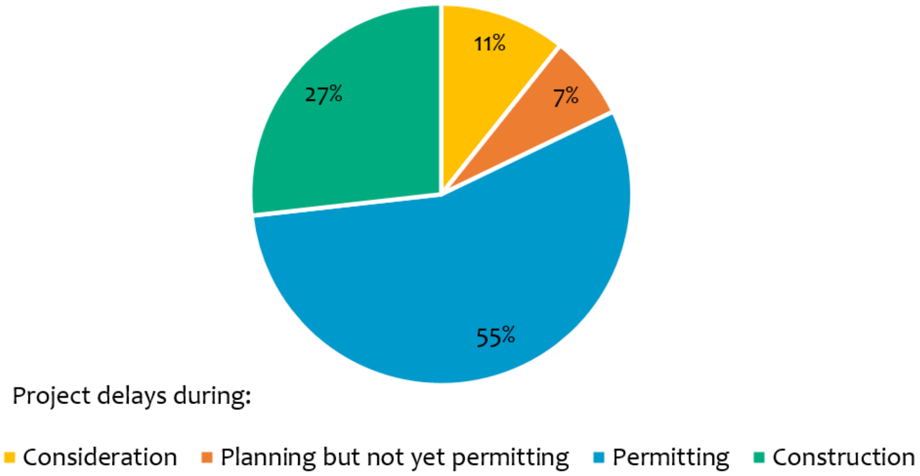

Figure 19: Delays of transmission projects per project phase. n = 56 projects.

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, 2021), 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.

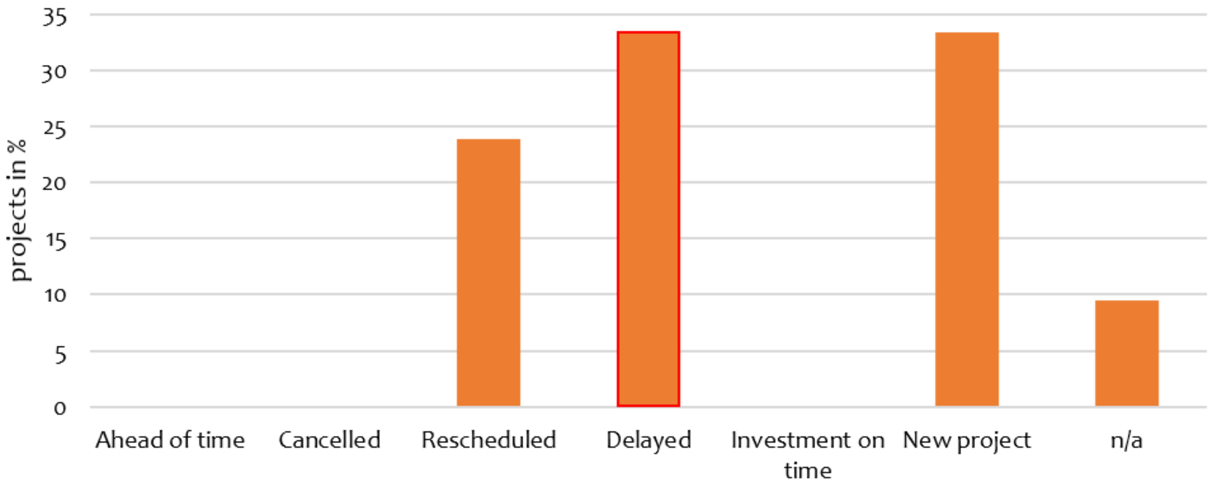

Figure 20: Progress of storage investments since TYNDP 2018, n = 21 projects.

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 Direcive 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
Citizen ownership developments	Electricity production capacity in MW by autoproducers[22] for wind, PV, solar thermal, wave/tidal/ocean energy Percentage of capacity by autoproducers for wind, PV, solar thermal, wave/tidal/ocean energy [%]	EU 28	Eurostat	Open

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[22] enterprises which produce electricity but for whom the production is not their principal activity

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**).

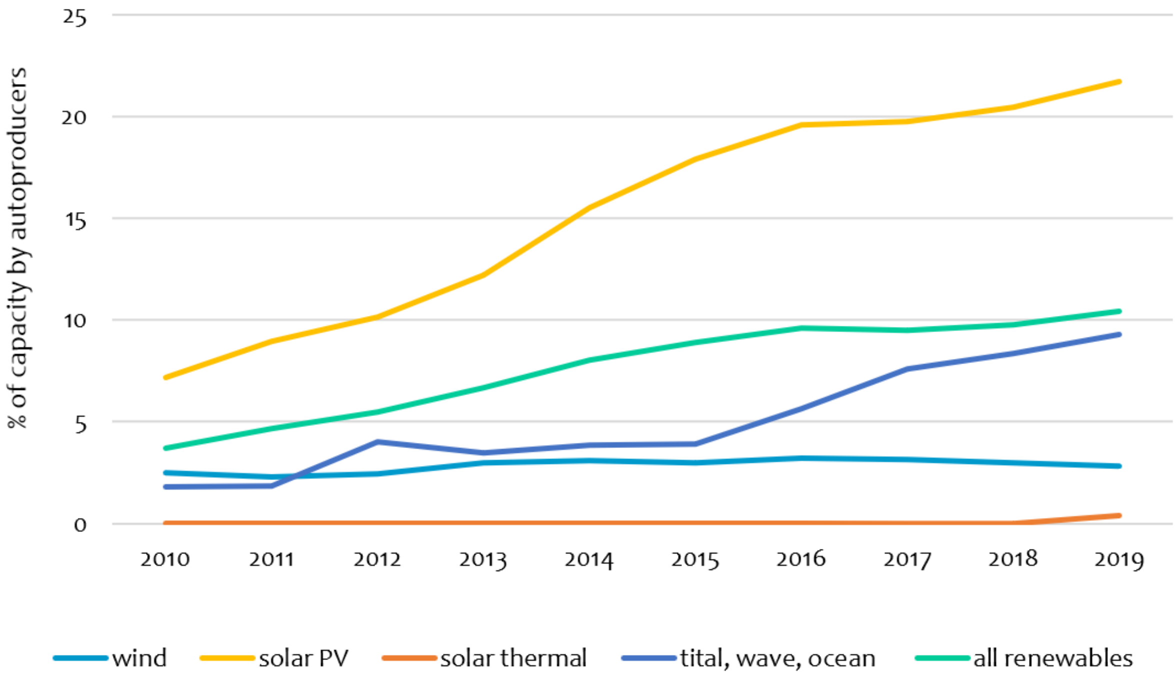

Figure 21: Development of autoproducers in the EU 28.

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

- The IEA[23] 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).
- In Germany, 40.4% of its citizens (individuals and farmers) own the installed renewable energy capacity[24] (AEE, 2017).

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[23] https://www.iea.org/reports/renewables-2019/distributed-solar-pv

[24] https://www.unendlich-viel-energie.de/studie-buergerenergie-bleibt-zentrale-saeule-der-energiewende

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 demands 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 two 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.

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)	EC-study, 2019	Open
Size of housing	Average number of rooms per person, annual Average number of rooms per person, annual	Eurostat, 2019 Eurostat2, 2020	Open

Further information on the 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.

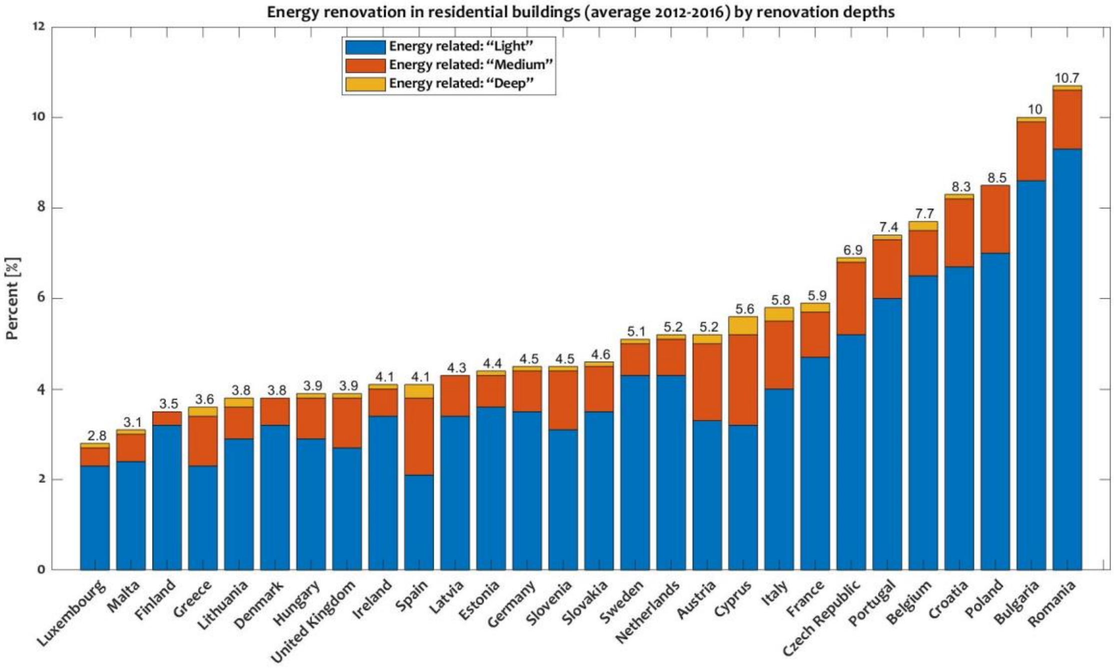

Figure 22: Energy renovation in residential buildings, sorted by overall renovation rate.

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.

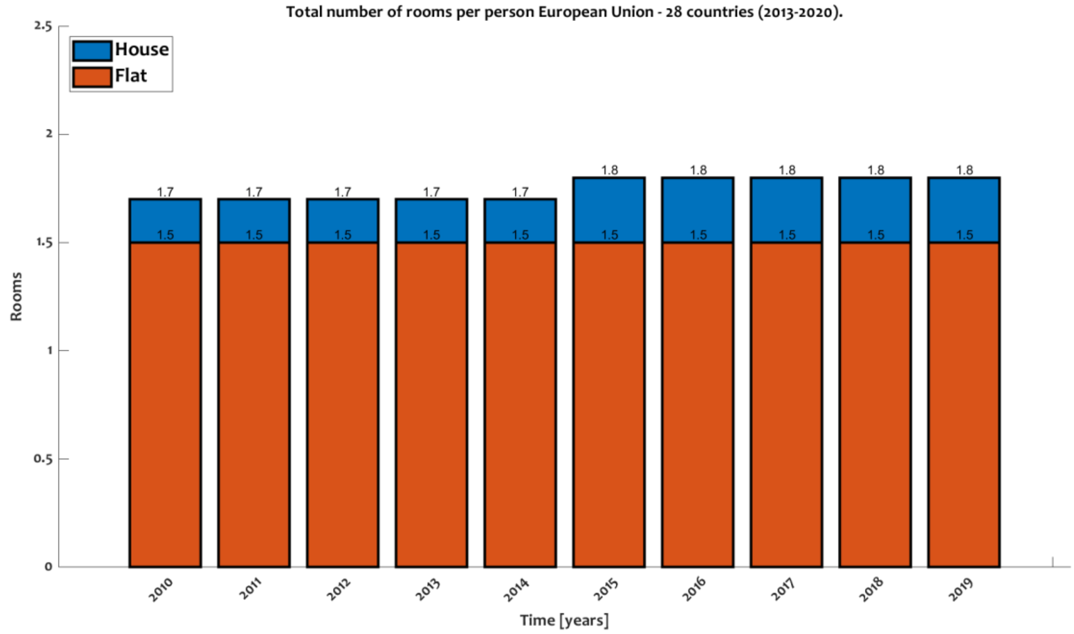

Figure 23: Total number of rooms per person EU 28.

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**).

4.3 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 fastest observed annual growth was in Montenegro with **7.6%** of total installed capacity in 2007 (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 7.5% 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 18-20**).

European case study

Table 18: Storyline variables and suggested quantifications for two policy pathways for the EU

Storyline variables & values	**People-powered**	**Market-driven**
Total GHG reduction targets	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)
Renewable energy in gross final energy consumption	>50% by 2030, 100% by 2040 (cf. Table 7)	32% by 2030, > by 2050 (cf. Table 6)
Energy intensity	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)
Fossil fuel phase-out	Coal by 2030 Fossil gas by 2035 Fossil oil by 2040 (cf. Table 7)	No fixed dates
Cross-border interconnection NTC	≥5% of yearly power production by 2030	≥15% of yearly power production by 2030 (cf. Table 6)
Residential building renovation	1% per year	3% per year (cf. Table 6)
Electric mobility	>20% reduction in car use (cf. Table 7)	0% reduction in car use

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 Marked-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-put, 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 19: Storyline variables and suggested quantifications for two policy pathways for the Nordic countries

Storyline variables & values	**People-powered**	**Governments-directed**
Total GHG reduction targets	Carbon neutrality by 2035 (cf. Table 9)	-70% (GHG-1990) by 2030 (cf. Table 8) Net-zero emissions by 2045
Renewable energy in gross final electricity consumption	100% by 2040 (cf. Table 10)	55% by 2030; 100% by 2050 (cf. Table 8)
Fossil fuel phase-out	Coal by 2029 (cf. Table 9)	Coal by 2030 (cf. Table 8)
Energy intensity	-25% energy intensity decrease (compared to 2005) by 2030	-50% (compared to 2005) by 2030 (cf. Table 10)
Residential building renovation	1% per year (current trend, cf. section 4.2.6)	3% per year (cf. Table 9)
Electric mobility	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

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 20: Storyline variables and suggested quantifications for two policy pathways for Greece

Storyline variables & values	**People-powered**	**Government-directed**
Total GHG reduction targets	Climate neutral by 2050	-43% relative to 1990 by 2030 74.7% relative to 1990 by 2050 (cf. Table 12)
Renewable energy in gross final energy consumption	100% by 2050	35% by 2030; 67.6% by 2050 (cf. Table 12)
Share in renewable energy and gas	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 21 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 21)

Fossil fuel phase-out	Coal by 2025 (cf. Table 12)	Coal by 2025 (cf. Table 12)
Energy efficiency intensity	-25% (compared to 2005) by 2030	>38% (compared to the forecast by 2030) and lower total demand than in 2017 (cf. Table 12)
Energy storage: installed capacity	≥15% of yearly power production by 2030 (cf. Table 6)	2.2 TWh by 2030, 8.2 TWh by 2050 (cf. Table 12)
Residential building renovation	0.72% per year (current trend, cf. section 4.2.6)	3% per year

(continued table)

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 21**, cf. **Figure A 7, Appendix 2**).

Table 21: Share of installed electricity capacity in Greece, assumed based on NECP and Long-term strategy 2050 targets in GW

	2030		**2050**		**2050 without gas**	
Unit | Renewable energy source	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 22**).

Table 22: 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 23**.

Table 23: 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 **24**, 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 24**). In this storyline, citizens support renewable energy, but local opposition is decreasing because of the decline of conditions for public participation and ownership.

Table 24: 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%
Total					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 25** summarises the key variables and quantifications in the context of the three storylines.

Table 25: 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

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 26** summarises the key variables and quantifications in the context of the three storylines.

Table 26: 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 24)	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 24** (next page). 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).

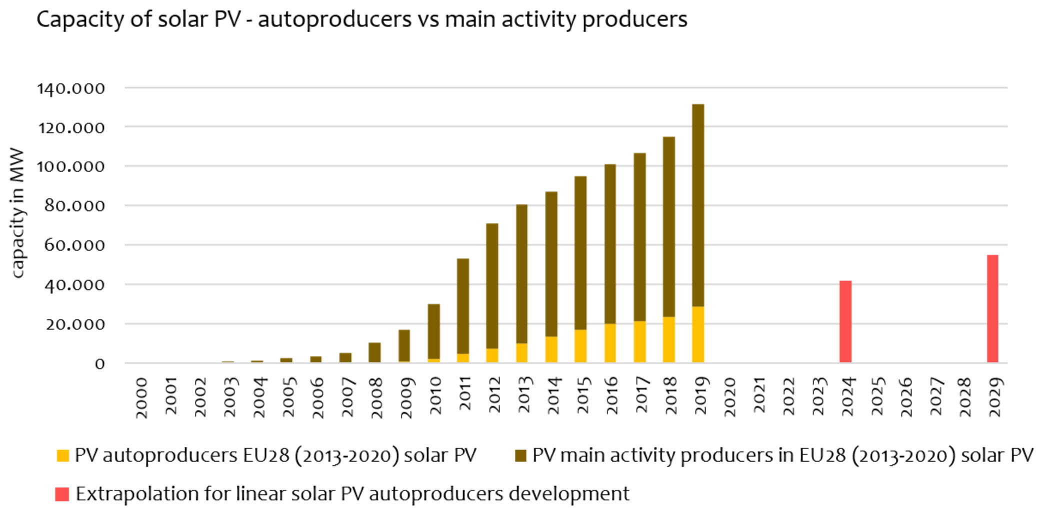

Figure 24: Potential future development of PV autoproducers.

4.3.6 Private energy demand & service

For each storyline, we assume different developments for building renovation and rooms per person. **Table 27** summarises the key variables and quantifications.

Table 27: Storyline variables and quantifications for private energy demand & services

Storyline variables & values	**People-powered**	**Government-directed**	**Market-driven**
Building renovation	Overall renovation of 1% annually (current trend, cf. section 4.2.6)	Renovation rate of 3% of which 70% are deep renovations (Table 7)	Overall renovation of 5% annually
Rooms per person	House: 1.7, Flat: 1.2 (trend Belgium for EU, cf. section 4.2.6)	House: 1.8, Flat: 1.5 (status-quo EU) (cf. Figure 23)	House: 2.1, Flat: 1.9 (trend Hungary for EU, cf. section 4.2.6)

Explanation. In the Government-directed storyline, we assume a renovation rate of 3% per year, with a higher focus on deep renovations, as in the Market-driven scenario. The living space per person remains as it is today.

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. To make full climate neutrality more achievable despite the lower renovation rate, the living space 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 strongest 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.

5 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.

Our deliverable has two major contributions to the SENTINEL project, and modelling work beyond:

- Social storylines, based on transitions theory and empirical observation of actual social/political drivers and barriers in the European energy transition
- 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.
    - Adapted in the way modellers see as appropriate for their particular scenarios and research questions.

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 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 defendable 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.

In the coming months, we will apply the storylines and data of QTIDIAN in different models and further deliverables in SENTINEL to generate new insight drawing on SENTINEL model improvements combined with the social storylines and related datasets. As it addresses both supply and demand-side factors, QTDIAN can be used by different model types, such as energy system and energy demand models, and it will be used by several models, including in the case study modelling of SENTINEL WP7. This report is the first step to include social and political factors in the energy models of SENTINEL. As we apply the storylines and quantifications, we will stay in close contact with the modellers and, where appropriate, incorporate their feedback on both usefulness and data consistency into updated versions of the QTIDIAN toolbox to make it even more useful and impactful for the continued work with the SENTINEL model suite.

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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

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 counties 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).

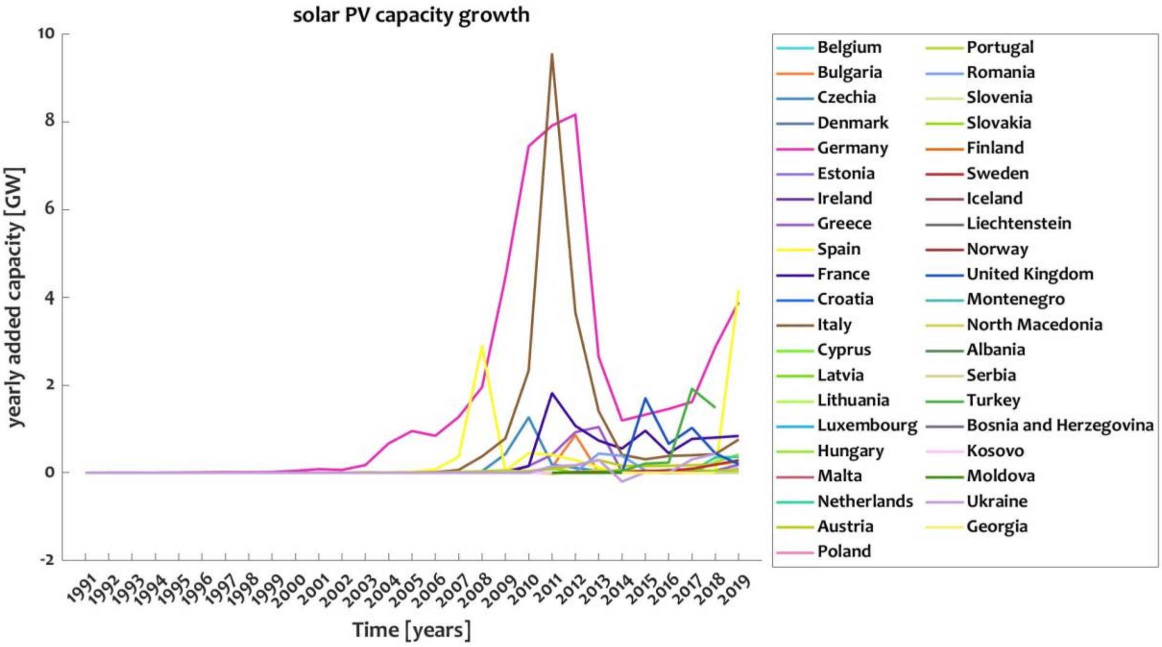

Figure A 1: Solar PV capacity growth.

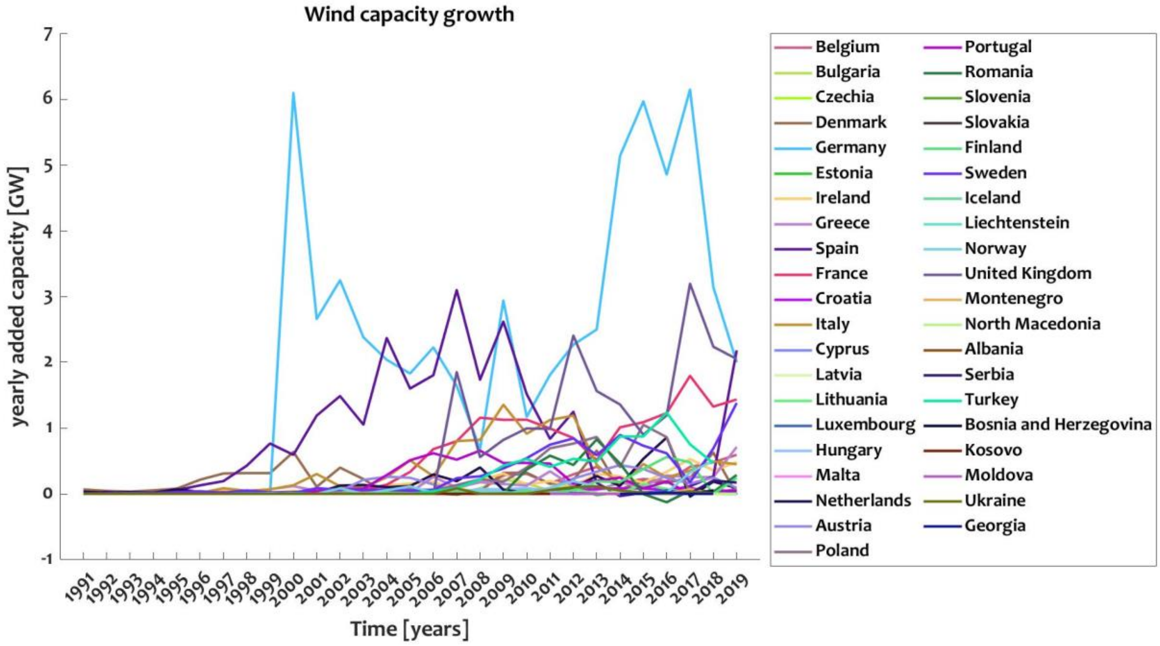

Figure A 2: Wind capacity growth.

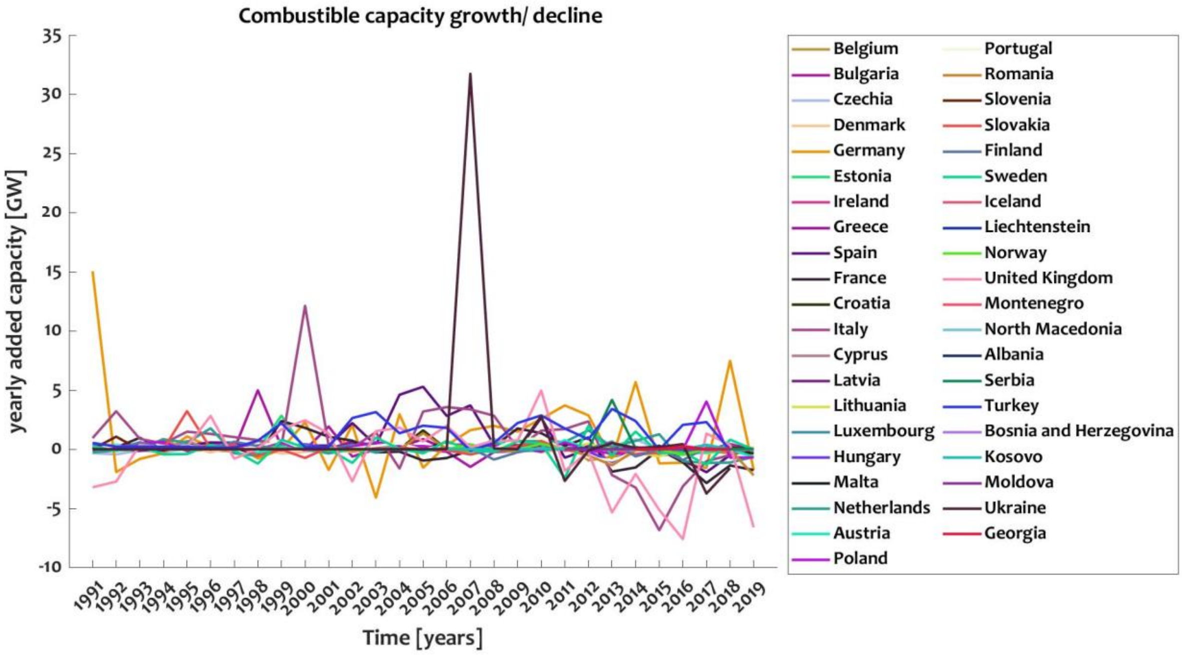

Figure A 3: Combustible capacity growth/decline.

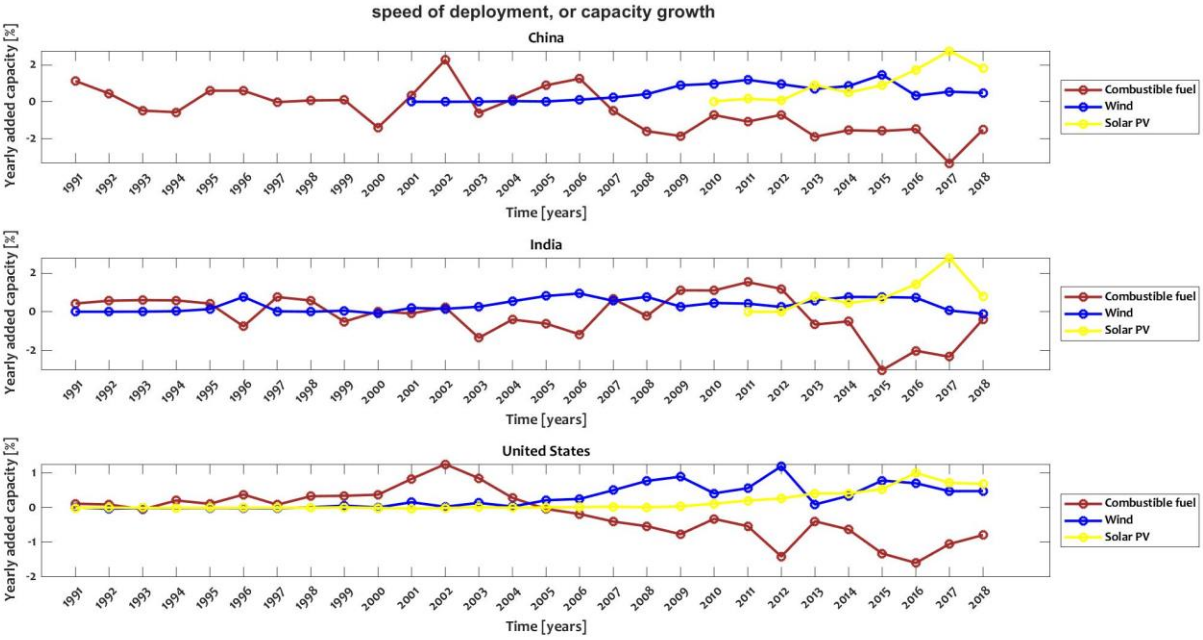

Figure A 4: China, India, the US capacity growth as Percent/ system change

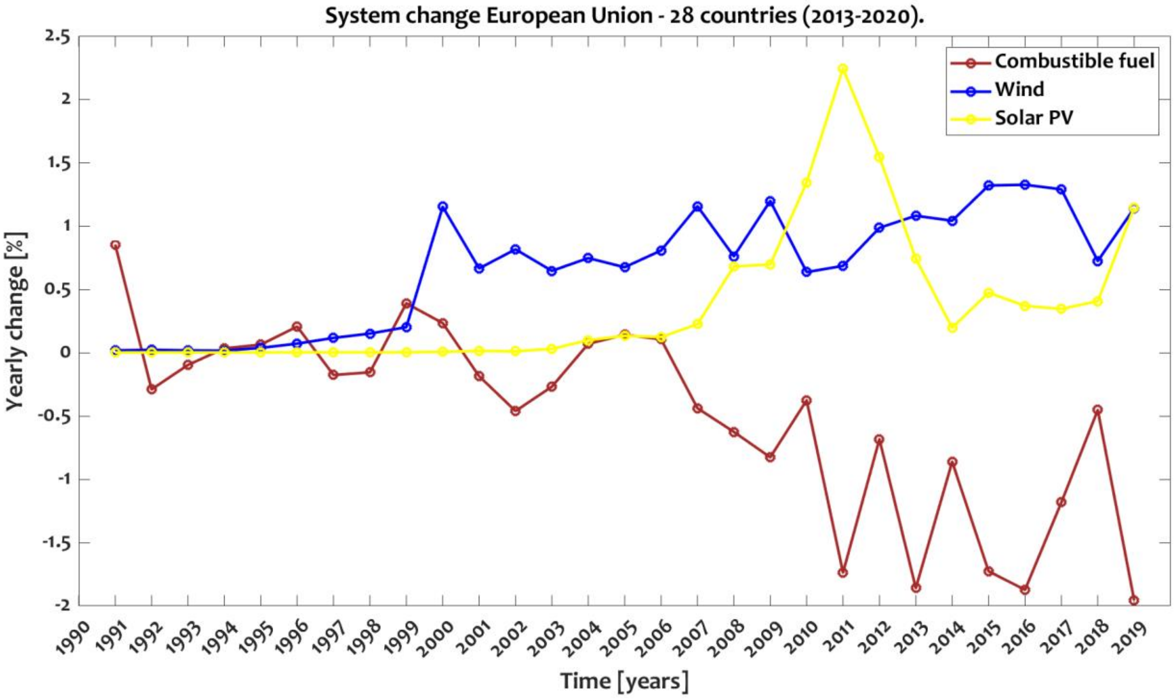

Figure A 5: System change EU 28.

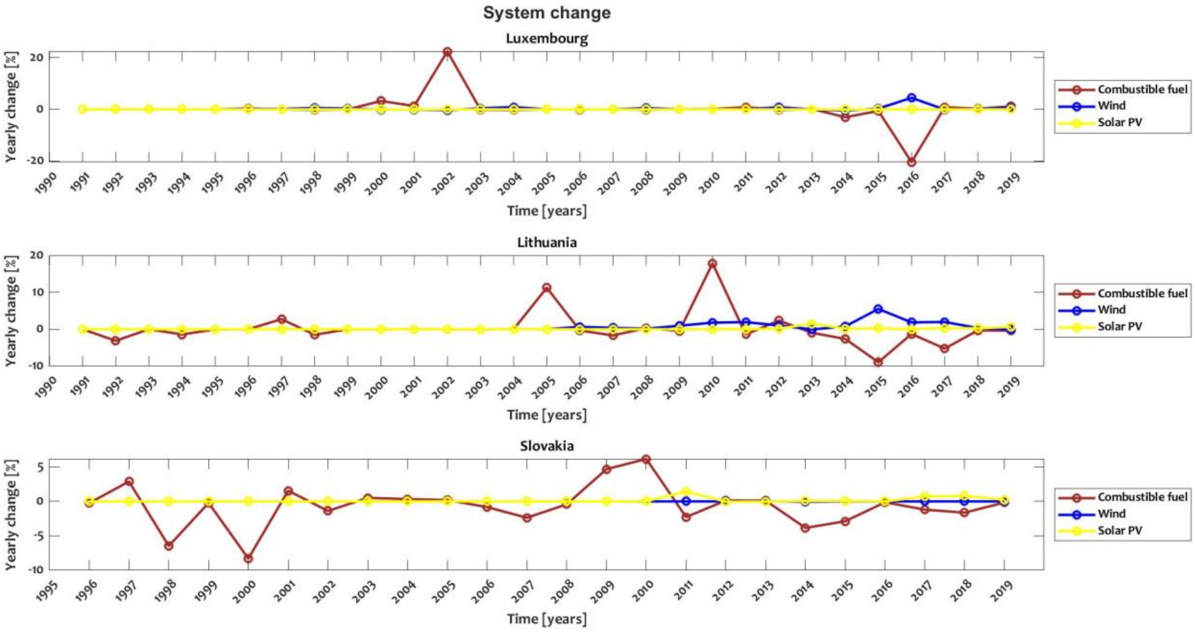

Figure A 6: Luxembourg, Lithuania and Slovakia system change: combustible fuel decline.

Appendix 2 Policy preferences & dynamics

Policy strategies

Data analysis. We analysed and used results from the SENTINEL Deliverable 7.1 (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.

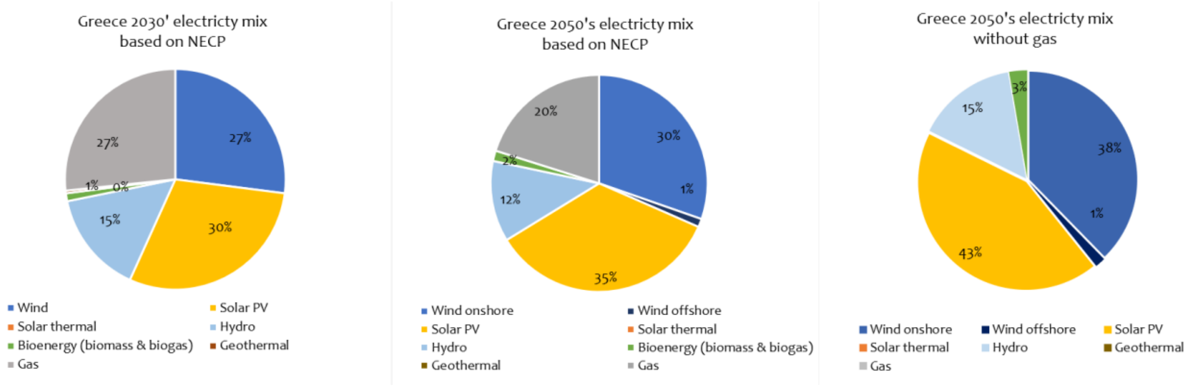

Figure A 7: Share of installed electricity capacity in Greece, assumed based on NECP and Long-term strategy 2050 targets in GW

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 basked" 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.

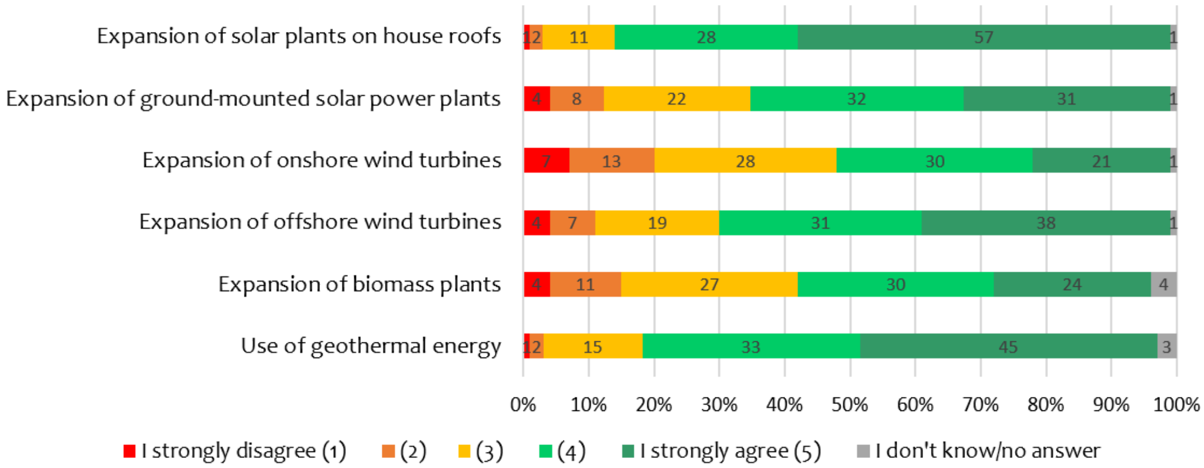

Figure A 8: Personal stance for the expansion/ use of certain technologies, survey from 2019, n = 6,117 households, Germany.

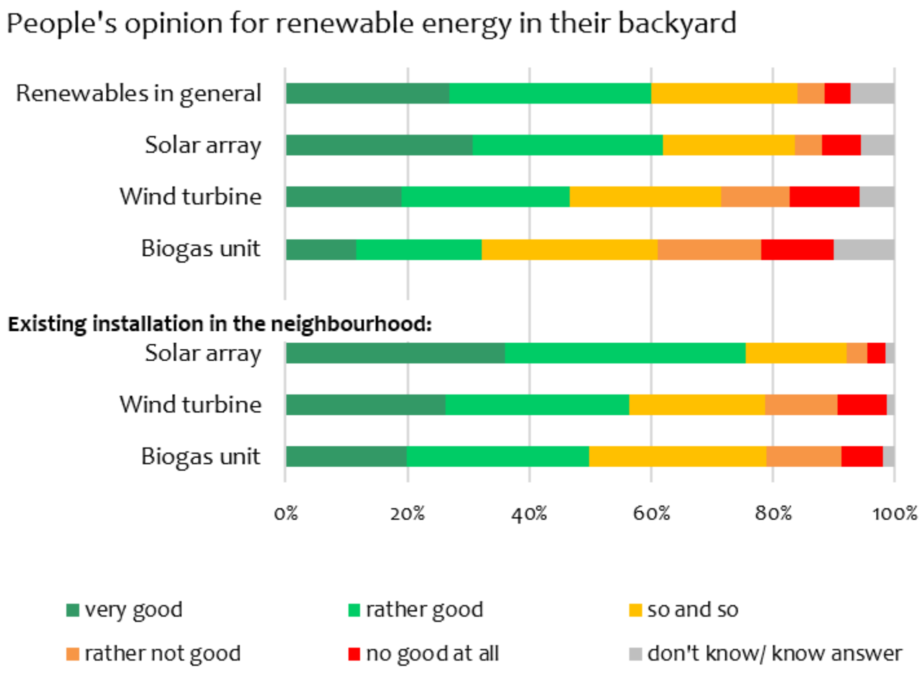

Figure A 9: People's opinions about renewable energy in their backyard, survey 2020, n = 1051, Germany. Data source: YouGov conducted for Agentur für Erneuerbare Energien.

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).

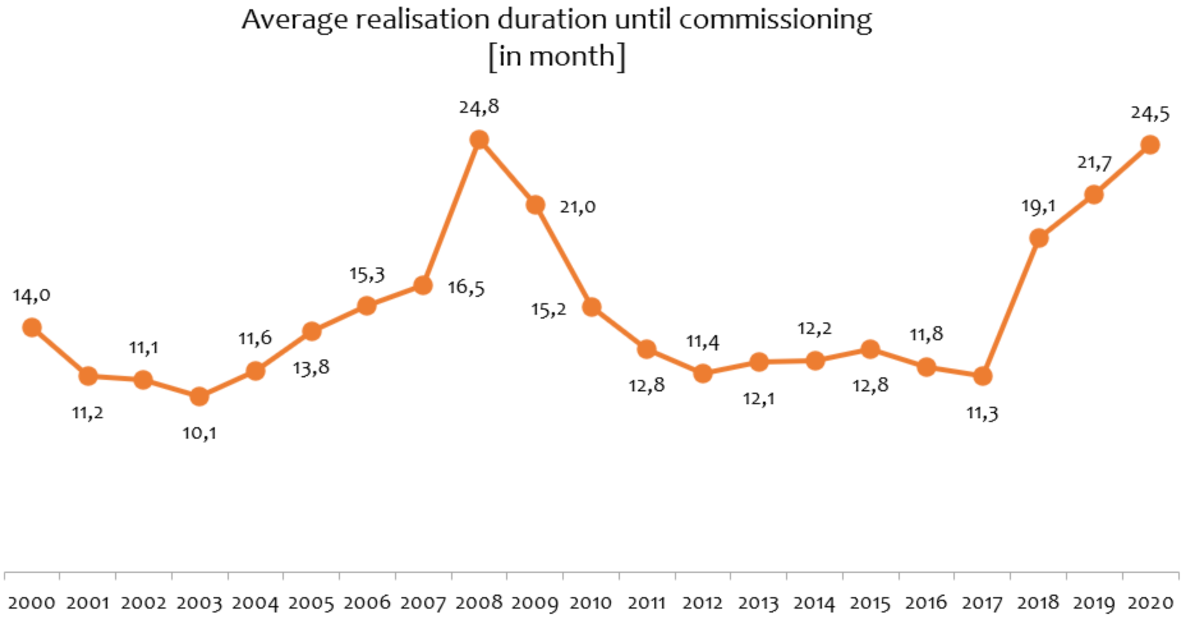

Figure A 10: Average realisation time for wind energy projects in Germany.

Table A 1: Litigation of approved wind power plants on land. Source: Fachgentur 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	**28**
Bayern	26	75.6	7	59	182.0	44	**42**
Brandenburg	28	77,9	7	213	681.4	13	**11**
Hessen	26	75.1	7	61	190.4	43	**39**
Mecklenburg-Vorpommern	15	47.5	4	111	335.3	14	**14**
Niedersachsen	45	139.1	13	225	746.6	20	**19**
Nordrhein-Westfalen	48	164.3	15	227	758.0	21	**22**
Rheinland-Pfalz	18	55.9	5	100	305.3	18	**18**
Saarland	3	9.0	1	14	37.3	21	**24**
Total	228	709.0		**1,080**	**3,471.0**	21	**20**

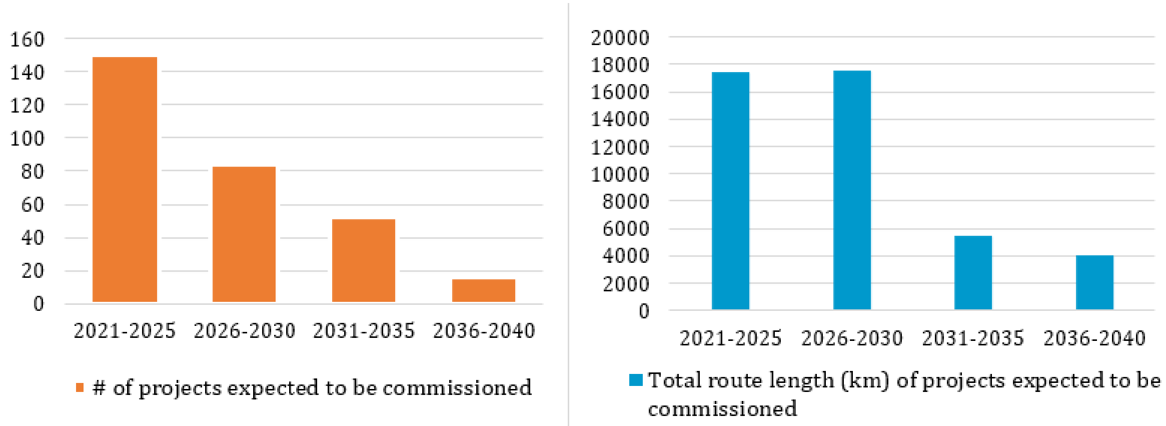

Figure A 11: Expected grid developments in numbers and lengths, according to TYNDP (ENTSO-E, 2021).

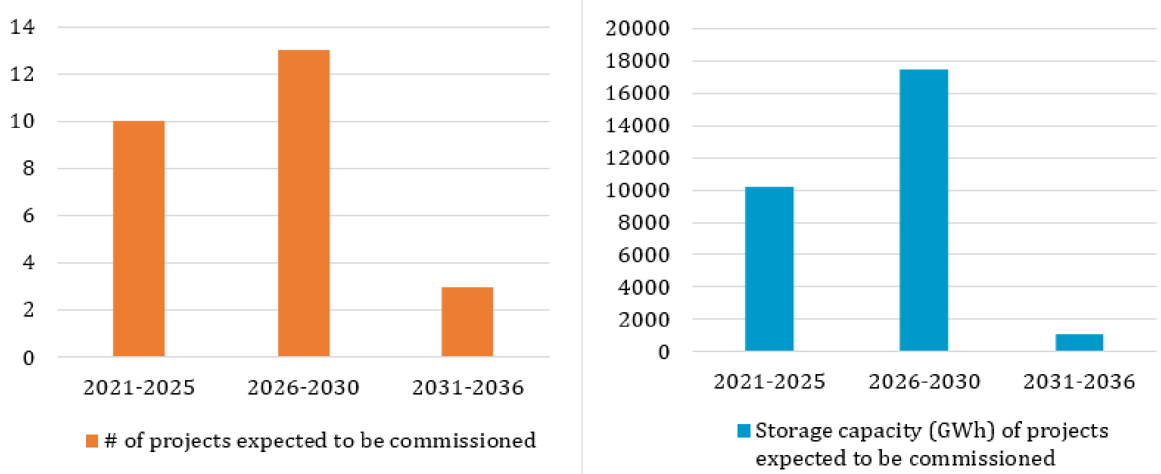

Figure A 12: Expected grid developments for storage in numbers and capacity, according to TYNDP (ENTSO-E, 2021).

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.

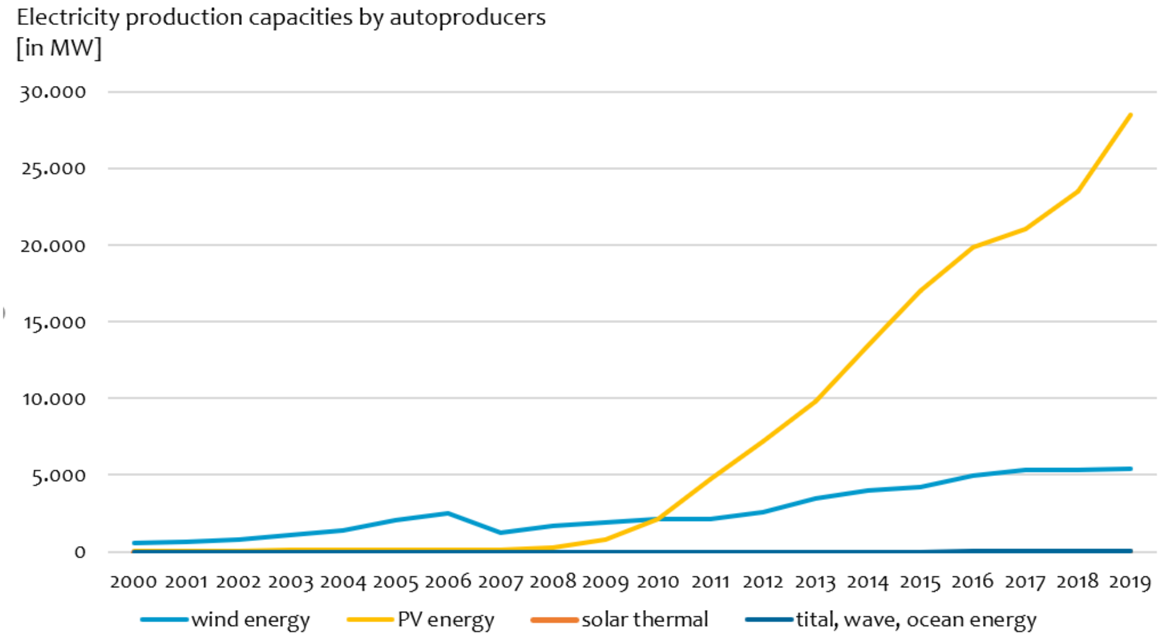

Figure A 13: Electricity production capacity by autoproducers in the EU 28. Note: the graph for solar thermal lies behind the graph for tidal, wave and ocean energy.

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."[25] 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.

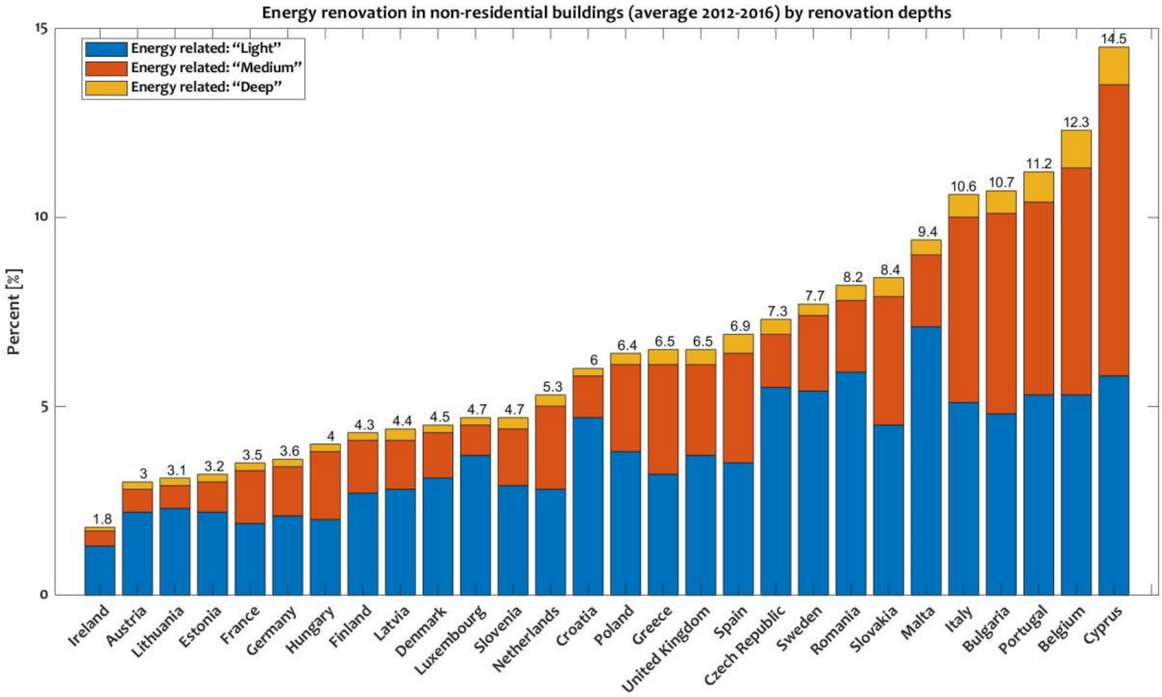

Figure A 14: Energy renovation in non-residential buildings, sorted by overall renovation rate.

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[25] https://ec.europa.eu/energy/content/setting-3-target-public-building-renovation_en

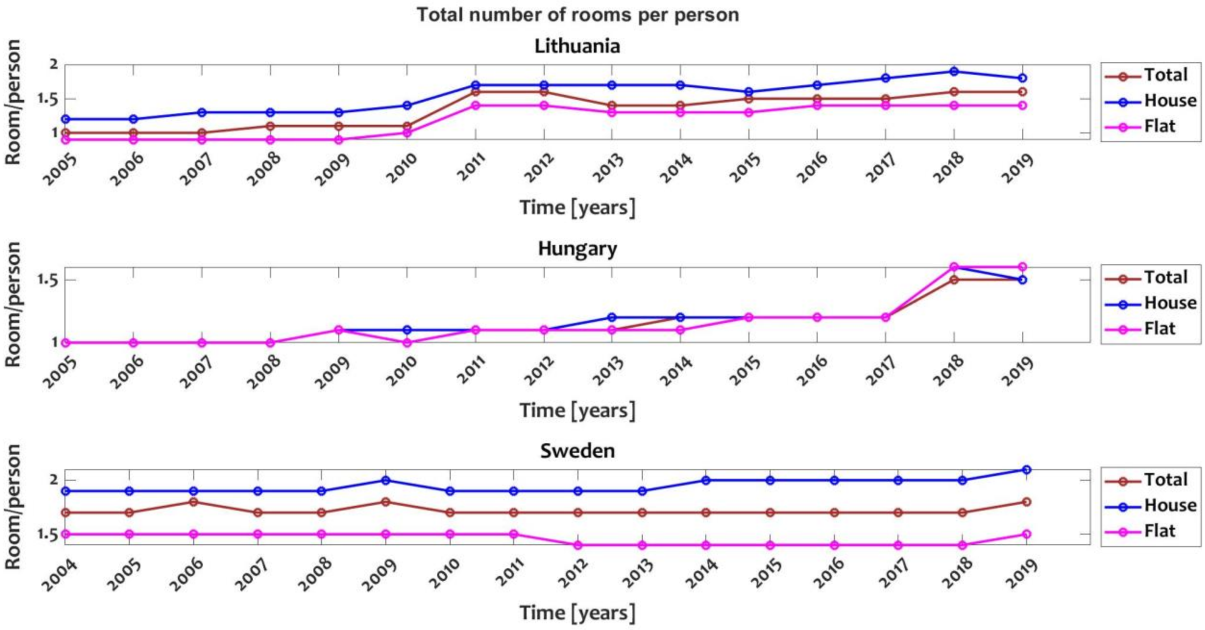

Figure A 15: Lithuania, Hungary, Sweden total number of rooms per person.

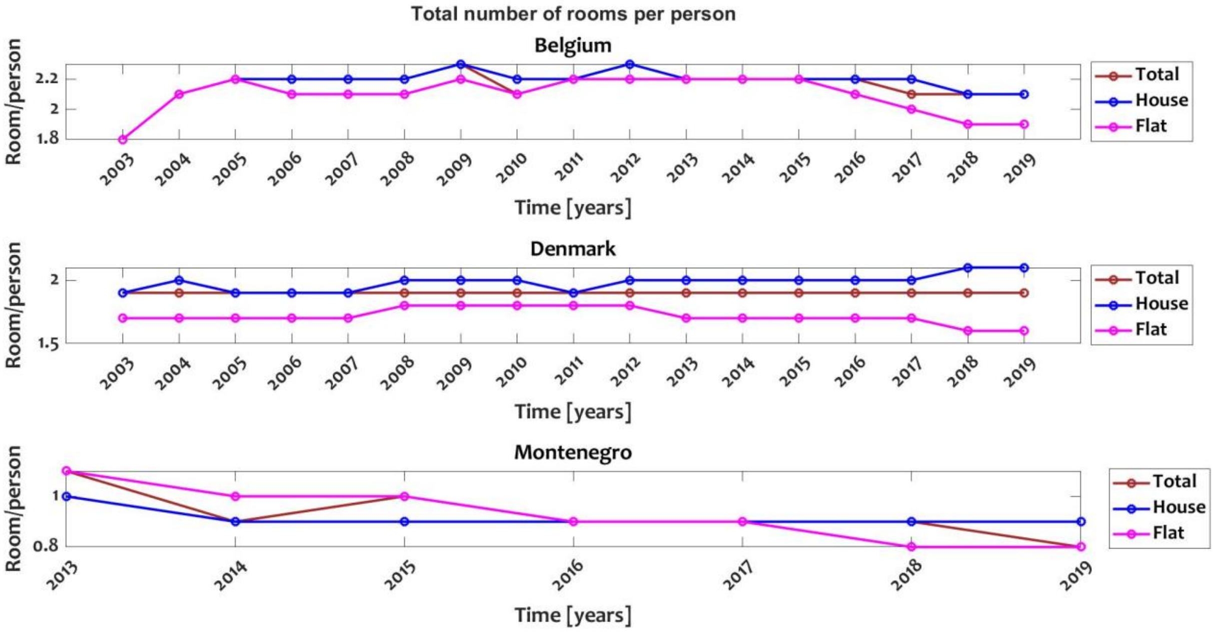

Figure A 16: Belgium, Denmark, Montenegro total number of rooms per person.