Policy Measures that Address Barriers and Market Failures in the Low-carbon Transition

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List of abbreviations

AEEL	Annual Expected Generation Lost
AEENS	Annual Expected Energy Not Served
BAU	Business-as-Usual
BH	Buyer of Hydrogen
CES	Constant Elasticity of Substitution (production or utility function)
CGE	Computable General Equilibrium
DSO	Distribution System Operator
ESS	Energy Storage System
FiT	Feed-in Tariffs
IEM	Internal Electricity Market (Directive)
IMO	Independent Market Operator
KLEM	Production structure composed of Capital, Labor, Energy and Materials
PTG	Power-to-Gas
RED	Renewable Energy Directive
SAM	Social Accounting Matrix
SME	Small-Medium Enterprises
TPA	Third Party Access
TYNDP	Ten Years National Development Plan

Contents

Executive summary

The fight against climate change requires profound changes in how we produce, distribute and consume goods and services. Such endeavor requires a revolution under both technological and societal dimensions and is studded with potential obstacles. The barriers limiting the pace at which the needed social and technological transformations are happening arise in different stages of the transition and from different sources on local or global scale. This document focuses on the description of the directions that could be considered to address the aforementioned barriers and facilitate the transition to a low-carbon society. The analysis of the potential barriers is performed starting from an individual viewpoint where the potential barriers related to the behavior of the individuals are identified and discussed. Then the focus moves towards the business dimension, where it concentrates on the potential barriers that could limit the proliferation of new business models related to flexibility and peer-to-peer solutions to the local management of energy consumption and production. Next, the attention shifts to the study of bigger aggregates considering both the technical aspects and the welfare-related aspects, where the focus is placed on understanding what is the impact of the widely used global least-cost solution towards different Countries and sectors involved in the transition process. The analysis is carried out considering how the least-cost solution of a long-term energy system model suggests operating to decarbonize the European energy system and benchmark this suggestion with the actual possibility that the considered countries have to carry out the plans suggested by the optimization tool. Finally, an array of macroeconomic analyses of the effects of different types of barriers, from political to technological, is performed, as well as using the combination of a macroeconomic general equilibrium model and a long-term energy system model to understand which type of impact a decarbonization effort might have on the sectoral activities and on the economic growth of the European countries. Factoring in the actor dimension in the process of transition to a low carbon energy system should lead to the definition of policy directions that address issues such as fair access to energy, job creation and economic development, and community engagement. Citizens behavior can define a barrier or an enabler to such transition. In general, the openENTRANCE storylines tend to see the society as an enabler to the energy transition, whereas the barriers can normally occur due to market inefficiencies or over regulation. In this respect, the oucome of the conducted survey sheds light on the fact that the driver perceived to carry the least amount of barriers for the communities is the technological one, while direct policy requirements are seen as the ones with the lowest acceptability. More particularly the citizens tend to be more engaged in the energy transition when it is not forced by law or taxation schemes, but rather supported by financial incentives for the adoption of energy efficient new generation technologies and facilitated by education initiatives for the usage of renewables and by standards encouraging the use of renewable energy. Actors tend to view more favourably any option that make clean technology more affordable and accessible. When looking at the business model dimension, many of the barriers are related to the current lack of business roles that should operate in sector coupling. As a mention, to couple the hydrogen and electricity sectors, an Hydrogen Agent should be considered. In this case there is need for more clarity related to ownership and operation of PTG devices such as electrolysers, compressors and hydrogen storage facilities. Moreover there is no shared definition for PTG which is considered concurrently a conversion service operated as a natural monopoly and a commercial activity. The lack of definition of key actors creates obstacles also in the business model for energy communities. This might lead to delays in investments. Other types of barriers related to the demand side are centered on network pricing for ancillary services such as frequency regulation and how it

may act as an obstacle to the utilization of resources within the energy community. Definition of the new roles and responsibilities is needed also for the business model for Web-of-Cells to ensure local balance and voltage control through internal trading of resources. Regulation should ensure that such key roles are defined and the relative responsibilities assigned. The welfare distribution dimension has shown that the modelling framework tend to define very high targets for capacity expansion with the result of having capacity expansions that exceed the size of today's power generation system manyfold. This might constitute an important barrier and should be addressed by adjusting the pathways. On a household level, solutions leading to sharp and fast changes in the employment might be subject to become entrenched. The measures need to be country-specific and well communicated to lead to beneficial outcomes for the affected country. Finally, on a macro-economic level the main results shed light on the fact that technological development is key to the transition towards low carbon solutions and that regulatory aspects need to support the uptake and diffusion of new technology and promote cooperation, rather than penalize players that have not year caught up with the transition; this is further highlighted by the fact that calling off the decarbonization agreements by countries rich in fossil resources might bring economic benefits to those countries. This underlines how the decarbonization effort needs to be defined as a collective effort based on mutual help rather than on penalty mechanisms.

1 Introduction

Climate change and environmental safeguard pose themselves as one of the greatest challenges faced by society. Even though the identification of the problem dates back several decades, to date the level of emissions keeps rising, and focusing attention on such an issue is more important than ever. There is wide consensus on the desirability of a transition towards a low-carbon economy albeit it is still not clear whether this transition can be carried out by effectively decoupling the decarbonization goals with the upholding of economic growth. It is nevertheless accepted that the achievement of green growth can be unlocked by the diffusion of clean technologies ([1], [2], [3]). Hence, a steadily growing number of countries have engaged in the implementation of policies targeting the reduction of GHG emissions, not only limited to the definition of carbon pricing mechanisms but encouraging research and development of low-carbon technologies. Nevertheless, the development and deployment of such technologies is slowed down by a number of factors with the most important being the limit on the financial resources that are allocated to foster the energy transition. Clean technologies require a substantial amount of investment which calls the public and the private sector to concur in providing the necessary support.

1.1 Background

The overarching technological barrier that the diffusion of clean technologies is facing is represented by the lock-in on existing standards, which in turn is upheld by the insufficient technological maturity of candidate solutions. This lock-in is mainly related to the perception of potential market failures as a consequence of investments in clean technology. The policymaker should aim at increasing the diversification in the portfolio of technology mix by factoring in the environmental aspects of technology policy and allowing the usage of early-stage financial instruments such as private R&D grants or crowdfunding on technologies characterized by this high uncertainty on the returns. This can be efficiently implemented by, as a mention, defining strategic partnerships between industry, academia, national laboratories and other governmental and non-governmental entities ([4], [5], [6], [7]). The scale required and the difficulties in harmonizing the private and public initiative to make new technologies competitive with the current ones has implied that the investments into R&D, commercialization, and diffusion of clean technologies remain nowadays at unsatisfactory levels ([2], [8], [9], [10], [11]). The pathway towards a successful transition of the energy and economic system towards a low-carbon structure requires therefore a solid package balancing policy, energy efficiency, and regulatory framework that can facilitate a reallocation of the investments towards a low-carbon energy mix. A second kind of barriers are the institutional ones. Those barriers are associated with a lack of regulation making room for the efficient deployment of clean energy solutions such as social rules and norms that favor fossil fuel-based technologies. Many studies suggest removing this institutional lock-in through the clearing of information asymmetries between the agents responsible for the research, development and deployment of low-carbon technologies. This could entail enforced cooperation involving high-quality universities, research laboratories, and technical institutes with the policy maker ([12], [13]). Typical issues belonging to the institutional barriers are represented by the ownership and management of the infrastructure. A lack of regulation on the definition of key roles that operate with the infrastructure might lead to difficulties in evaluating the commercial viability of low-carbon solutions. The policymakers should provide regulatory support to facilitate the development and the operations around the infrastructural assets ([14],

[13], [15]). Regulatory barriers do not only pertain to the infrastructure sphere but extend more in general towards several aspects of the development and uptake of low-carbon energy solutions. As a mention, legal security and uncertainty related to policy changes represent serious risks for investments in the energy transition. Besides institutional barriers, local and environmental acceptance of low-carbon technologies plays another important role in the diffusion of these solutions. Negative attitudes of the local population toward the deployment of clean technological solutions are well-known and documented in several countries. The NIMBY issue as well as the preservation of local landscape or different use destinations for land and sea pose important pressure against the development of low-carbon solutions. Moreover, the diffusion of clean technologies might be hindered by the lobbying activities of the players drawing benefits from the usage of incumbent technology, who might influence regulatory action. A third class of barriers to an effective decarbonization process is represented by economic barriers. Namely, innovative technologies are usually less convenient than older fossil-based counterparts because these latter do not normally incorporate their negative environmental effects in their prices ([16, 17]). Moreover, there is uncertainty about the appropriability of novel technologies in terms of economic exploitation, which results in lack of investments and funding for R&D ([18], [19], [20]). Generally, a lack of business models for radically new technologies introduces challenges related to investments that might prevent a commercial deployment of the technology. Finally, the savings on which many technologies depend are dampened by artificially low energy prices due to subsidies to fossil fuels ([5], [16], [17], [21], [22]). A last class of barriers is represented by political barriers. Those relate directly to the competencies and mandates of the policymakers involved in the innovation process for clean technologies. These kinds of barriers refer to a lack of multi-level policy coordination across different systemic levels, normally between institutions operating at different levels such as regional, national, or European levels, leading to mismatches between the directives given at different levels. But these barriers can also be related to a lack of horizontal coordination, i.e. between Science, Technology, and Innovation (STI) policies and sectoral policies as well as between different ministries and implementing agencies ([12]), which leads to missing coherence between the actions performed at those different levels. Such policy coordination failures might lead potential investors to withdraw their contribution to the development of the technology already under the very initial phases. As shown in Figure 1, each of the aforementioned barriers can affect the development and deployment of low-carbon technologies in different stages of their life cycle. In particular technological barriers are usually present in the first stages of the development, from the R&D activities to the demonstration of the functionalities, while institutional barriers become a problem only from the pre-commercial phase on. Economic barriers are almost absent during the R&D phase, but materialize under the demonstration phase and become gradually more important as the technology reaches the commercialization phase.

1.2 Objectives and scope of this deliverable

This deliverable discusses the effects that potential barriers and incentives can have on the development of low-carbon technologies. These barriers and incentives will be analyzed from a multidimensional perspective starting from a local and individual scale and reaching the systemic energy and macroeconomic level. Namely, under the individual perspective, called the "actor dimension", the barriers and incentives are initially considered based on the impact that they exert on the end-users decision-making to understand the extent to which the model results reflect actual human decisions. From this individual-based perspective, the analysis will move

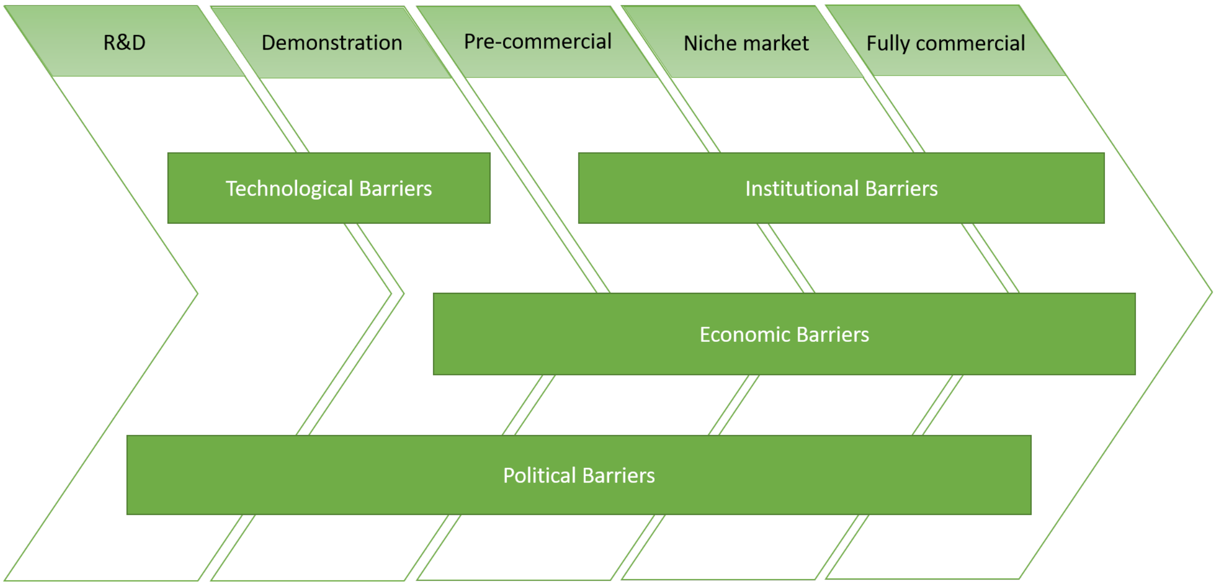

Fig. 1: **Types of barriers and span of their influence in the development and deployment of low-carbon technologies. (adapted from [23])**

to a slightly more collective dimension by considering the impact that incentives and barriers have on the formulation of business models and on their economic viability in what has been defined as the "business model dimension". At the widest and most comprehensive level, the analysis will consider the effects on the socioeconomic system with the "welfare dimension"; this is done with the objective of understanding whether the widespread least-cost approach used by several classes of system models is compatible with a general increase in the welfare of the society or if there are situation in which some actors come out with welfare losses that makes it unlikely for a particular solution to be selected as a potential policy as it presents barriers to decarbonization. Finally, the different types of barriers aforementioned will be studied from a macroeconomic viewpoint to highlight the impact that they have on the main economic KPIs such as the development of sectoral value added. For each considered dimension, the study of the impact exerted by drivers and barriers on the development of low-carbon technologies will be framed in one or more of the openENTRANCE scenarios (Gradual Development, Societal Commitment, Techno-Friendly, Directed Transition).

1.3 Structure of this report

The remainder of the document is structured as follows: Chapter 2 will focus on the impact of barriers and drivers under the actor dimension, Chapter 3 will identify and discuss drivers and barriers, and under the business model dimension, Chapter 4 will discuss the identification of drivers and barriers under a welfare dimension, while Chapters 5 and 6 will discuss the impact of these drivers and barriers under a macroeconomic aspect as well as under a coupled macroeconomic and energy system perspective.

2 Actor dimension

In the energy transition, technological development and strong policy push to phase out fossil-based power generation will be key enablers to achieve a carbon neutral energy system. However, the energy consumer, the citizen or the 'small actors might be the central driver, and the ultimate decision makers to accelerate or delay the adoption of new technologies. The consumer, small actors, or average citizens can raise public support to enact ambitious climate policies. Therefore, the importance to understand the role of the citizen (and the society) as a barrier or enabler to the development of policy measures that support the European energy transition.

In this regard, in the openENTRANCE project, four storylines describing the energy transition to a low-carbon energy system have been developed looking at: the role of strong policy initiatives, perspectives on technological progression, and the influence of societal attitudes (or the 'actor dimension'). That is, these scenarios or storylines have been developed by looking at the drivers and developments that these create in shaping a possible future (Pathway for the energy transition). This is illustrated in Figure 2 where we observe that *Smart Society* describes the situation where society is concerned about climate change, changing their habits as consequence. *Policy Exertion* assumes that there is a push on new regulation and environmental policies. *Technological Novelty* is related to new green technologies, characterized as low costs and high benefits. These three factors, combined as couple of drivers, define a scenario to reduce 90% to 100% Green House Gases (GHG) emissions. In addition, a conservative scenario combines all key drivers to reach 80%-90% reduction of GHG emission. Different sets of drivers result in four scenarios (or storylines that once quantified are transition pathways), these are Societal Commitment, Techno Friendly, Directed Transition, and Gradual Development. A thorough explanation of the openENTRANCE Project and the scenarios are available at [24, 25, 26]. These scenarios have been quantified and analyzed using energy system modeling approaches in the openENTRANCE project.

In these pathways and scenarios towards a European decarbonized energy system, **smart society** is seen as one of the cornerstone to the realization of the energy transition by relying on environmental friendly attitudes and actions from the public and society in general. Smart society envisions the engagement and awareness of the society to take concrete actions to combat climate change. This driver assumes that there will be a strong support from the public and active participation (climate activism) on changing attitudes and behavior in lifestyles. There, from the actor dimension perspective, understanding the energy transition is seen from two different storylines: i) Techno-friendly and ii) Societal Commitment. The central assumptions and notions of these are as follows:

- **Societal Commitment** : Strong societal engagement and awareness of the climate crisis among citizens. They support strong policy measures to become a low-carbon society. But in this storyline, there are minimal technological breakthroughs, so it relies on policy push combined with societal engagement.
- **Techno-Friendly** : The carbon-free technologies have good progression and development and are well welcomed by citizens. This storyline is driven by citizen awareness and initiatives taken by the industry sector which deliver new technologies. However, political decisions are slow or minimal.

These storylines are scenarios quantified in the openENTRANCE project. Modeling results and analysis derive understandings on what the central drivers needed to develop pathways for

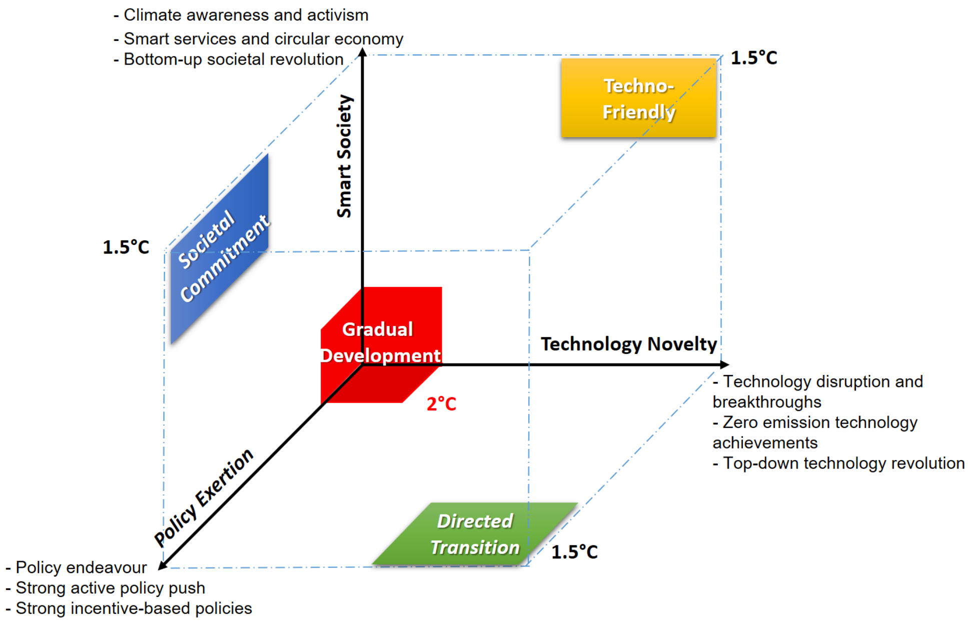

***Fig. 2:* Pathways storylines typology = policy exertion x technological novelty x smart society. The three dimensions set the scene on three disruptors or uncertainties which together creates four storylines (colored squares).**

the European Energy Transition. This is first quantified in the GeneSysmod model (Deliverable D3.2), see [26, 24]. However, energy system modeling approaches and techniques centered on results from the 'modelling framework' might have limited reflections on the implementability of the storyline and its main assumptions. For example, given that the two storylines described above rely on active societal engagement, how likely is it that the 'energy system model' results reflect actual human decision-making? That is, how the modeling frameworks represent the transition of the energy system taking in consideration human perception (or the actor dimension). To understand this dimension, in this chapter, we take a closer look at model results that aim to represent aspects of a smart society and the role of actors' (societal) collective energy choices. We analyze the two storylines focusing on aspects of a "smart society" to discuss whether modeling results are in line with how individuals might take decisions. This contributes to identify barriers based on the suggested decisions in the models and discuss possible deviations from human decision-making.

The model used to analyze the two openENTRANCE storylines is the EMPIRE model, described in [27]. EMPIRE features two stages: one investment stage and one operational stage, thereby characterizing it as a capacity expansion model focused on the European power system. EMPIRE has been used in a number of publications, and EU projects [27, 28, 29]. The model represents the EU countries in addition to Switzerland, Norway and Balkan countries. Export and import of electricity is possible in neighboring countries and zones. Investment decisions in generator capacity, energy storage, and transmission are done in EMPIRE to facilitate production in order to meet the demand in the modeled region on an hourly basis without exceeding a carbon emission cap. Electricity demand, technology costs, technology options and operational characteristics are inputs [28]. The output is given as investments in technologies and operational decisions assuming a perfect competition market. EMPIRE is a linear capacity expansion model, spanning over multiple decision (2025-2060) periods of 5 years each. Each period is composed of 4 regular seasons, representing winter, spring, summer and autumn, and two peak seasons representing extreme conditions. Each regular season has 168 hours and each peak season has 24 hours. Uncertainty is included in every hour for load and generator availability for VRES. Data, assumptions and other specifications for the EMPIRE model are based on the implementation of the openENTRANCE storylines [30, 26].

2.1 A smart society in the European decarbonization of the power system

This section analyzes the European energy system transition based on two of the above-mentioned pathways: Techno-Friendly and Societal Commitment. As mentioned, both of these pathways assume positive attitudes in society towards the energy transition. So, the modeling results of these pathways expect a strong role and limited barriers from the actor dimension. Note that these two pathways lead to different generation mixes, but both attain the goal of limiting the temperature increase to 1.5° C.

Figure 3 depicts both the annual expected generation and installed capacity of various generation resources for the Techno-Friendly and Societal Commitment pathways from 2025 to 2060 divided into five-year time intervals.

The first explicit observation is the significant increase in the capacity and annual production of wind energy in both pathways over time. The wind production alone will be more than the aggregated production of other resources in the fourth period (i.e., 2035–2040) for the Societal Commitment pathway and the seventh period (i.e., 2050–2055) for the Techno-Friendly pathway. It is also clearly observable that the realization of these two pathways requires a large reduction in the annual generation of the resources that emit carbon dioxide. This statement only does not hold for lignite-based generation in the Techno-Friendly pathway and, to a smaller degree, for gas-based production in the Societal Commitment. These two points are elaborated on later in this section. To present a clear picture of the energy transition based on these pathways, an important metric to consider is the following:

$$A_1 = \frac{\text{Annual Expected Generation Lost (AEEL)}}{\text{Total annual expected generation}} \times 100 \tag{1}$$

where AEEL is the production of non-dispatchable renewable resources—wind, PV, and hydro run-of-the-river—that cannot be utilized (because the load is less than the generation) or stored (due to the lack of capacity or charging rate of available energy storage systems).

Table 1 shows this metric together with some other key metrics for some selected five-year time intervals. These metrics were calculated on the basis of the total annual expected generation. To analyze this table, it is necessary to emphasize two points:

- **P1:** Carbon dioxide emission in these two pathways for the five-year intervals must be limited as per Figure 4.
- **P2:** Technologies based on Carbon Capture and Storage (CCS) are not available in the Societal Commitment pathway.

Similar trends: As discussed, the main common trend between these two pathways is the significant investment in renewable energy resources. Wind production will dominate the

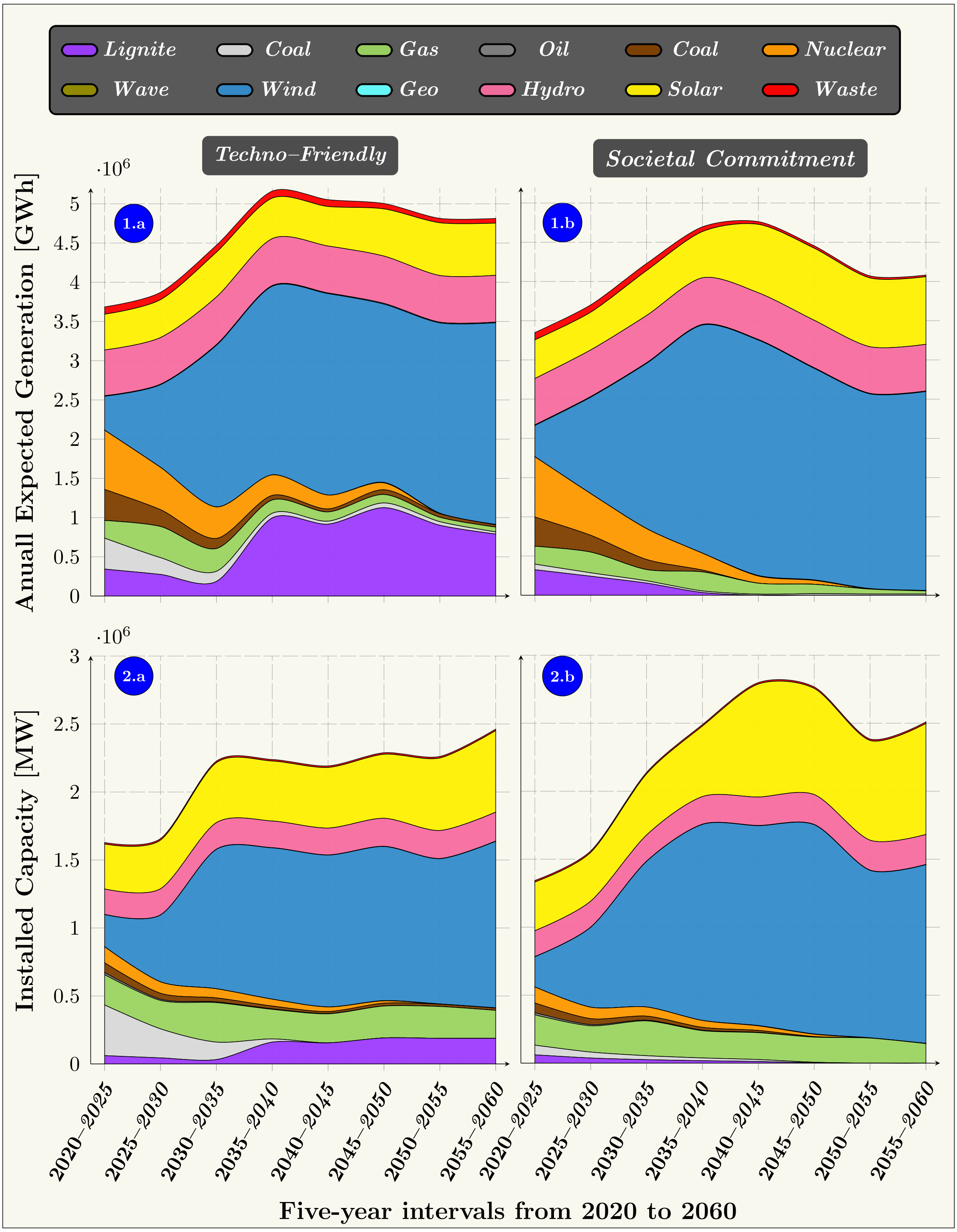

Fig. 3: **European energy transition: 1) Annual Expected Generation of various resources for the Techno-Friendly (1.a) and Societal Commitment (1.b) pathways. 2) Installed capacity of various resources for the Techno-Friendly (2.a) and Societal Commitment (2.b) pathways.**

***Table 1:* Key metrics of Techno-Friendly and Societal Commitment pathways for some selected five-year time intervals.**

Employed pathway	Five-year intervals	A_1 [%]	Loss load [%]	Wind production [%]	PV production [%]	G5* production [%]	Annual Storage** discharge [%]	CO2 emission [ton]
Techno-Friendly	**2025–*2030***	1.02	–	26.3	12.1	35.6	1.7	903.3
	2035–*2040*	3.6	–	45.4	9.7	28	2.3	495.4
	2045–*2050*	3.78	–	46	11.9	27.4	2.5	264
	2055–*2060*	8.54	–	53.4	13.9	18.3	2.8	110
Societal Commitment	**2025–*2030***	0.94	–	30.3	11.8	30.8	2	867.5
	2035–*2040*	10.29	–	59	12	10.5	2.5	330
	2045–*2050*	15.27	–	59.3	20.2	3.7	5.4	55
	2055–*2060*	17.89	–	61.2	20.8	0.94	6.6	22

*G5 production: Aggregated production of lignite, coal, oil, gas, and nuclear-based generation units.
**Aggregated discharge of both considered storage systems: Li-Ion BESS and hydro pump storage system.

European energy system in both pathways by 2060. Another common trend is the need for non-renewable energy resources in both pathways even during the interval 2055–2060. However, their dependency on non-renewable generation differs regarding both the type and capacity of these resources, which is discussed in the next paragraph.

Dissimilar trends: As seen in Figure 3, the Techno-Friendly pathway chooses to invest in lignite and gas-based generation resources to compensate for the variability of the non-dispatchable renewable generations. Between the two resources, this pathway mostly utilizes lignite-based generation resources to produce energy. This is the main difference between these two pathways. A question arises then: *why does the Techno-Friendly pathway choose to make a high investment in lignite-based generation while the Societal Commitment pathway makes no similar investment?* The answer can be found in P2 (pointed out above). Due to the availability of lignite-based generation with CCS technology in the Techno-Friendly pathway, it uses this advantage and invests in this resource to compensate for the intermittency of non-dispatchable renewable energy resources. Conversely, since such an option is not available for the Societal Commitment pathway, it chooses to invest in gas-based generation resources to cope with the randomness of non-dispatchable energy resources. However, the annual expected generation of gas-based units is limited to meet the tight constraint of the carbon dioxide cap in this pathway.

Also, the Societal Commitment pathway requires higher investment in storage systems to cope with the intermittency of non-dispatchable generation resources. This point can be seen in Table 1 in which the annual discharge of storage systems increases to 6.6% of the total annual generation in the Societal Commitment pathway during interval 2055–2060 compared to 2.8% for the Techno-Friendly pathway.

In addition, note that the share of non-dispatchable generations that cannot be utilized in-

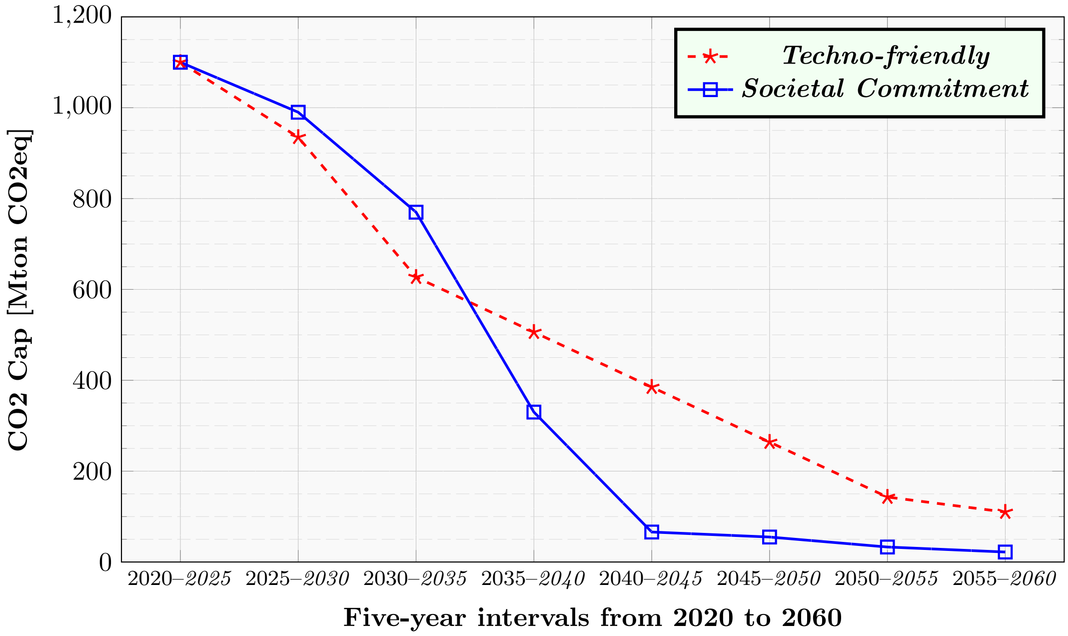

Fig. 4: **Comparison of CO2 Cap between the Societal Commitment and Techno-Friendly pathways**

creases in the course of time in both pathways. This has been reflected through metric A_1 in Table 1. As can be seen, this increment is much larger in the Societal Commitment pathway—17.89% versus 8.54% in the Techno-Friendly pathway. This is due to the great reliance of the system on non-dispatchable energy resources in the Societal Commitment pathway. Compared to the Techno-Friendly pathway, the greater reliance of Societal Commitment on non-dispatchable energy resources is due to two reasons: First, in the Societal Commitment pathway, we must decrease the CO2 emission to 22 Mton during the interval 2055–2060, which is much lower than 110 Mton in the Techno-Friendly pathway. Second, dispatchable energy resources that can benefit from CCS technologies are not available in this pathway.

Reflections on the actor dimension

All in all, we observe that these modeling results and decarbonization pathways heavily rely on societal support and engagement. *Societal commitment* achieves faster and stronger decarbonization as it assumes that the actor dimension (or the citizen) is supportive or aligned with the policy directives for a green transition. Societal commitment combines the best of policy push and smart society, hence a combination that focuses on harmony, synergies, and interaction between these two. This insight and implications might be difficult to explain from energy system modeling perspectives and results. Meaning that non-effective policy measures could be drawn as they might focus on the end-point (2050), i.e., model results. This might disregard or take for granted the role of the actor, the citizen, the civil society, and the 'actor' in general. As the pathway has a strong dependence on policy-society collaboration, policy measures should focus on addressing any barriers related to market inefficiencies and over-regulation.

As for *Techno-Friendly*, the transition takes a more bottom-up approach compared to the societal commitment. Smart society drives the energy transition with low involvement or impact from policy directives. Results from an "actor dimension" perspective primarily assume that there is low-resistance on technological change and positive attitudes on its adoption. Here the barriers will be related to the affordability of technologies and deregulation.

2.2 Model results and human decision making: individual, collective and social perspective

As detailed in the modeling results, commitment from society ('smart society') is central to decarbonize the energy system because it ensures that there is widespread support and engagement in the transition to low-carbon energy sources. This can involve individuals, businesses, and governments taking a range of actions to reduce their carbon footprint and support the adoption of clean energy technologies. These actors can help to drive the necessary policy and regulatory changes needed to accelerate the transition to low-carbon energy sources. Governments and policy makers are more likely to prioritize and invest in clean energy technologies if there is strong public support for these efforts.

Policy developments aligned with societal engagement might be a central pillar to build momentum and drive innovation in the energy transition. As more individuals and businesses adopt clean energy technologies, it can create demand for these products and encourage further research and development in the field. This might drive down the costs of clean energy technologies, making them more accessible and affordable for a wider range of users. In short, policies that develop or stimulate a collective societal engagement might be central to build a sense of community and shared purpose around the transition to clean energy. In this regard, policies and initiatives that promote "working together" or encourage collective societal engagement in the energy transition might be, for example:

- A wider carbon pricing scheme. By putting a price on carbon emissions, governments can create an economic incentive for individuals and businesses to reduce their carbon footprint. This can include carbon taxes, cap-and-trade systems, or other pricing mechanisms.
- Renewable energy and energy efficiency incentives: Policy can offer financial incentives to encourage the adoption of renewable energy technologies, such as solar panels or wind turbines. This can include subsidies, grants, tax credits, and feed-in tariffs.
- Public education and outreach: Governments and other organizations can engage in public education and outreach efforts to raise awareness about the importance of the energy transition and how individuals and businesses can contribute.
- Community-level initiatives: Local governments and community organizations can support initiatives that encourage collective engagement in the energy transition, such as community solar projects, energy cooperatives, and carpooling programs. This promotes engaging people at the grassroots level in the energy transition.
- Corporate leadership: Companies can take a leadership role in the energy transition by setting ambitious sustainability targets, investing in renewable energy, and engaging with stakeholders to drive change.

Individual versus Collective

Modeling results illustrated in the previous section also assume that there is a collective (group) behavior or action that facilitates the energy transition. However, individual actions shape group behaviors, and vice-versa. This creates uncertainty about "representing" and assuming collective decisions towards technology choices or policy preferences in energy system models. In a "Techno-Friendly" scenario, for example, it is debatable that a smart society will be *collectively* supportive of keeping lignite with CCS. However, the model's economics and technological choices find this logical. This analysis might bring some policy initiatives and agenda towards implementing this energy mix while falling short on identifying societal barriers to implement and support these.

Therefore, interpreting modeling results should look at barriers that take into account the joint-collective and individual viewpoints when analyzing the energy transition. This allows to consider the impact of the transition on different groups within society, and identify barriers. This includes not only the direct impacts on individuals and communities, but also the indirect impacts on social systems and institutions. Analyzing the social perspective ensures that the energy transition is equitable and inclusive. This means taking into account the needs and concerns of vulnerable and marginalized groups, and ensuring that they are not disproportionately affected by the transition. For example, identify any potential barriers or challenges that certain groups may face in accessing clean energy technologies or services, and develop strategies to address these issues. By understanding the social impacts of the transition, we can identify and address any potential concerns that different groups may have. For example, the transition to low-carbon energy sources may have impacts on employment or the economy for certain sectors or groups. In this regard, designing energy transition policies should ensure that the transition is fair and equitable for all members of society. Some of the key social considerations to minimize barriers to include:

- Fair access to energy: Ensuring that all members of society have access to reliable and affordable energy is essential for promoting social and economic development.
- Job creation and economic development: The energy transition can create new job opportunities and stimulate economic development in some areas. It is important to ensure that these benefits are shared fairly and that disadvantaged communities are not left behind.
- Community engagement: Engaging with and involving the local community in the energy transition process can help to build support and ensure that the transition meets the needs and priorities of all members of society.

Given these considerations and the openENTRANCE pathways' assumptions regarding the role of a 'smart society', what would be the most important driver from the three dimensions presented in Figure 2. To answer this question, a pilot survey[1] was conducted to openENTRANCE stakeholders to collect inputs on what are the barriers for the energy transition, the drivers, and the priorities (see more details in Chapter 5). In this pilot survey, a question related to the actor dimension, was *" What is the most important factor or driver that will determine a*

[1] A pilot survey was conducted to get an overall impression from a small group on the pulse of priorities and barriers relevant for the energy transition.

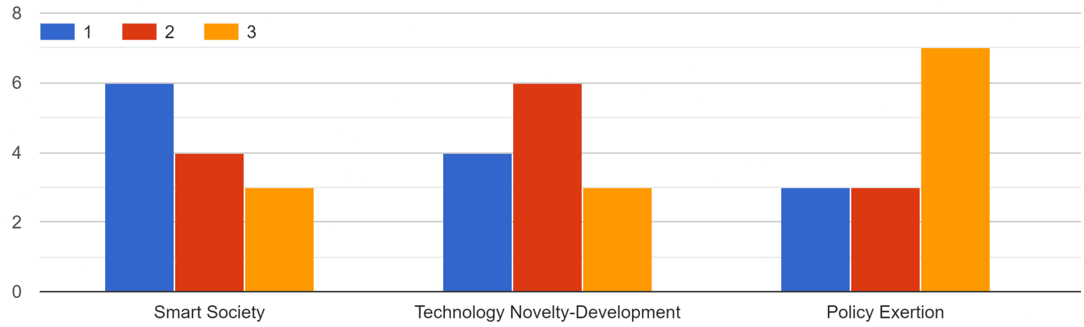

Fig. 5:* Response from openENTRANCE stakeholders on the question: *From your perspective, please rank the following drivers according to how strongly they influence or determine a successful decarbonisation of the Energy system. (1 = strongest influence, 3 = lowest influence)

successful energy transition in Europe?". The question aimed to capture to what degree stakeholders (policy makers, industry actors, and others) see the importance of the pathways' drivers (society vs technology vs policy direction).

Figure 5 summarizes the responses to this question. It is clear that the best-ranked option is smart society (blue bars), followed by technology development, and policy exertion as the last. This implies that stakeholders might perceive that Techno-Friendly as the pathway to face the least barriers. This is also evident in the second rating (Red bar), there stakeholders note technology development and smart society also as primary drivers, and again policy exertion comes as the last one. This implies that stakeholders have low expectations on policy initiatives and top-down decisions. Limited confidence in policy measures has been a recurrent challenge in the energy transition.

Techno-friendly is also perceived to be the one with the least barriers as it requires fewer policy measures compared to the other pathways. This might be explained given that one of the main challenges in decarbonizing the energy system is the high upfront costs and long-term investments that are required. These costs can be prohibitive for individual actors, such as households or businesses, and may require collective action and support to be viable (Bottom-up approach or grass-roots).

Energy system models limitations and the human dimension

Energy system models are good tools to analyze the behavior of energy systems, including the production, distribution, and consumption of energy. The EMPIRE model is a useful model to understanding the potential impacts of different policy and technology scenarios on the energy system. However, there are several limitations to energy system models in reflecting human decision making [31], for example:

- Complexity: Energy systems are complex and involve many interconnected components, such as power plants, transmission and distribution networks, and end-use appliances. It can be challenging to accurately capture all of these components and their interactions in a model, which can limit the model's ability to accurately reflect real-world energy systems. Here, the models usually takes for granted an assumption from the actor dimension (e.g., openENTRANCE pathways), but this is mostly disregarded or not analyzed.

- Assumptions: Energy system models often rely on a number of assumptions, such as future energy demand and technological progress, which may not accurately reflect the future course of events. Also, models assume technology adoption only based on economic grounds while not considering the collective perception of society and its effect on technology uptake.

- Human behavior: Energy system models typically do not account for the full range of factors that influence human decision making, such as individual and societal values, attitudes, and behaviors. This can limit the model's ability to accurately reflect the impact of policy and technology scenarios on human behavior and the energy system.

- Limited data: Energy system models are based on data from the past and present, which may not be representative of future conditions. In addition, data on energy systems can be incomplete or uncertain, which can limit the accuracy of the model's projections.

These and other limitations from energy system models create challenges to incorporate human behavior so as to better reflect the impact of policy and technology scenarios on the energy system. There should be a bridge between energy system modeling approaches and incorporating human decision making. For example, energy system models can incorporate behavioral models, which are mathematical models that aim to understand and predict human behavior. These models can be based on psychological theories and can take into account factors such as individual and societal values, attitudes, and behaviors. In addition to behavioral models, energy system models can incorporate data from surveys and experiments that ask people about their attitudes and behaviors related to energy use and the energy transition. Based on this information and other inputs, energy system models can work together with agent-based modeling, which is a modeling approach that simulates the behavior of individual agents (e.g., households, businesses) and their interactions within a system [31]. This approach can allow for the incorporation of more nuanced and complex representations of human behavior.

Overall, incorporating human behavior into energy system models might provide a better understanding and reflect the impact of policy and technology scenarios on the energy system. However, human behavior is complex and can be influenced by a wide range of factors, which can make it challenging to accurately incorporate into energy system models. Hence, the results of energy system models should have a more in depth post analysis that goes beyond the model's output.

2.3 Understanding Energy Choice Dynamics and Behaviors: Perspectives from ECHOES and Smartees research projects

Social norms and culture can also influence collective behavior choices when it comes to clean energy solutions. If a community or society places a high value on environmental stewardship, it may be more likely to adopt clean energy solutions. To understand this energy choices, behavioral theories propose that individuals make decisions based on a combination of cognitive, emotional, and social factors, rather than solely on rational considerations. For example, this could mean that presenting information about the cost savings of energy-efficient appliances in a way that emphasizes the benefits to the consumer rather than the environmental benefits could increase the likelihood that the consumer will make a more energy-efficient choice. Another example suggests that people are more likely to adopt energy-efficient behaviors if they believe that others in their community are also doing so. Overall, behavior theories can help to identify the specific factors that influence energy choices and provide guidance on how to design policies and programs that are more effective in promoting energy-efficient behaviors.

These aspects has been studied in the ECHOES[2] project, funded under the H2020 program. ECHOES focuses on understanding the energy behavior of citizens to improve acceptance, and impact of energy-related policies. The project has a social science perspective with a trans-disciplinary approach to research the citizen participation and engagement in the Energy Transition. After a significant data collection and analyses across 31 European countries, ECHOES identified three overall project insights and enablers in the actor dimension [32], these are :

- Reduce the regulatory barriers for joining in energy programs (e.g. energy communities) and offer support to individuals and groups to use and engage with a program.
- Build into energy programs standardized information and data collection tools and include indicators for social effects. The central outcome and objective is to ensure that this information is available to individuals and actors to allow them to understand their energy use and how it relates to the usage of others, as well as other factors (environmental, market, technology, etc.).
- Target policies towards specific collectives and groups of individuals with similar needs and characteristics. This will ensure group's uptake, support and acceptance of the policy (e.g. appealing to emotions, social identity and place attachment).

These insights are further corroborated and explored in the Smartees project[3], also a H2020 funded project. The focus centers on researching socially innovative and sustainable energy transition behaviors. Also in the Smartees project, the sharing of information is key to foster the acceptance of energy choices and related solutions. According to Smartees main findings, the project notes that municipalities will be the driving force behind social innovations. This is mainly because individuals are embedded in networks, and through them transmit their experiences and learn from others [33, 34]. Hence, local governments are seen as a core part of building trust as they could be a hub for social innovation (otherwise, distrust becomes a barrier). In this regard, the project results notes that encouraging local participation in the design process builds trust. It emphasizes that citizens should be involved early in the process facilitated with open and transparent communication as well as inform of improvements to living quality as a result of energy transition related initiatives.

In short, both ECHOES and Smartees insights reflect important aspects to consider in the development of a smart society (see Fig. 2) and the realization of transition pathways, i.e. Societal Commitment and Techno-Friendly. Specifically, some of the social innovation ideas to take into account for realizing these pathways could be:

- Community engagement and empowerment: Social innovation can involve engaging and empowering communities to take ownership of their energy systems and make decisions about how they are managed. This can increase commitment to the energy transition by making it a more locally relevant and meaningful issue. This will be particularly important

[2] ECHOES: Energy CHOices supporting the Energy union and the Set-plan, https://echoes-project.eu/

[3] Social innovation Modelling Approaches to Realizing Transition to Energy Efficiency and Sustainability, https://local-social-innovation.eu/

for the techno-friendly pathway where decentralization and adoption of technologies will be bottom-up driven.

- Creating new business models: Identifying attitudes and specific behaviors can also create new business models for clean energy, such as community-owned renewable energy projects, which increases investment and commitment to the energy transition. This must go hand-in-hand together with policy support as it is envisaged in the societal commitment pathway.

- Building awareness and education: Social innovation can also involve building awareness and education about the benefits of clean energy, and the potential negative impacts of fossil fuels. This can increase commitment to the energy transition by helping people understand the importance of the issue and the role they can play in addressing it. This something central for both Techno-Friendly and Societal Commitment as both rely on a smart society development.

- Leveraging technology: Social innovation can leverage technology to create new platforms, tools, and services that make it easier for people to access and use clean energy. This can increase commitment to the energy transition by making it more convenient and accessible. As noted earlier, it relates to have a more open and transparent information processes. For example, techno-friendly pathway relies on a rapid adoption as well as development of technologies, both will require new platforms and tools to understand their potentials and catapult their uptake.

- Creating shared values to develop a sense of collective responsibility for addressing the energy transition, which can increase commitment and engagement among different stakeholders. This relates to Smartees point on involvement of local governments and municipalities.

- Creating partnerships: Social innovation can also create partnerships between the public and private sectors, as well as between different organizations and communities, which can increase commitment and resources for the energy transition.

All in all, these indicate that decentralized decision making will be key driver to realize the Societal Commitment and Techno-Friendly pathways. That is, decentralized decision making allows for a more flexible and adaptive approach to the energy transition by allowing communities to experiment with different solutions and technologies that are tailored to their specific needs and resources. This might allow for better alignment of energy solutions with local context and needs, which can increase the chances of successful implementation and adoption of clean energy solutions. More importantly, a more decentralized perspective can provide a more democratic and inclusive approach to the energy transition by allowing communities and individual actors to play a more active role in shaping their energy future.

2.4 Policy suggestions and market-regulatory options to address investments barriers and determinants

The citizen plays a key role in the energy transition, as the demand for energy is driven by individual and collective actions. By making informed decisions about their energy consumption and choosing to support the use of renewable energy sources, citizens can help to drive the transition away from fossil fuels and towards a more sustainable energy system. This can include things like choosing to use energy-efficient appliances and lighting, supporting the development of renewable energy infrastructure, and advocating for policies that support the transition to clean energy. Ultimately, the success of the energy transition will depend on the collective efforts of individuals and communities to demand and support clean, renewable energy.

There are several policy options that can make the citizen more engaged in the energy transition, including:

- Implementing financial incentives, such as tax credits or rebates, for individuals and businesses that invest in renewable energy technologies or energy-efficient appliances.
- Establishing programs or initiatives that educate and inform citizens about the benefits of renewable energy and the importance of energy conservation.
- Developing regulations or standards that require or encourage the use of renewable energy, such as renewable portfolio standards or building codes that mandate the use of energy-efficient materials and technologies. Providing support and funding for community-based renewable energy projects, such as solar or wind farms, which can help to engage citizens and empower them to take action on renewable energy.
- Establishing programs that facilitate the transition to electric vehicles, such as vehicle rebates or charging infrastructure, which can help to reduce greenhouse gas emissions and improve air quality.

Overall, these policy options can help to increase citizen engagement in the energy transition by making it more convenient, affordable, and accessible for individuals and communities to support and adopt clean energy technologies.

3 Business Model dimension

3.1 Background and limitations of the study

Achieving the Pan-European goals for decarbonization of the energy sector requires several radical steps following the energy transition path. This also raises a need for the development and implementation of new business models, which employ advanced technologies enabling innovative business ideas. Hence, it becomes increasingly important to explore and validate the feasibility of these models and identify potential barriers, which may prevent successful deployment or limit their functionality. The main objective of this section is to explore the business model dimension, based on several factors including new developments of consumer participation in the market, energy communities and new roles of aggregators. The following assumptions have been used throughout the study:

- The study does not consider significant technical breakthroughs or complete technology stagnations, leading to deviations in the foreseen paths for the development and deployment of new technologies.
- Some of the business models are directly inspired by R&D projects and developed further. The models, however, are intentionally not country-specific, so they can be applied in most European Member States.
- The applied business modeling methodology allows evaluation of economic feasibility, by assignment of specific cash flows to value exchanges. However, due to an unknown development of costs over time, which are difficult to foresee, this part was excluded from the analysis.

The main terms and definitions used in the present section are explained in the Glossary (see Annex, Section 7.2).

3.2 Criteria for selection and development of the business models

One of the activities in the openENTRANCE project dealing with scenarios for low carbon futures in the European power system ([26]) pointed out the necessity of emerging and analysis of new business models.

Table 2: **Mapping scenarios and business models. Source: [26]**

Scenario	Directed Transition	Societal Commitment	Techno-Friendly	Gradual Development
Foreseen characteristics of the models	Partly different to status quo	Completly different to the status quo	Comparable to existing ones (based on economies of scale)	Partly different to status quo

One of the main challenges is to select very few, yet relevant and representative business ideas. The following selection criteria were applied:

- Contribution to the decarbonization of the economy by increased share of RES in the generation mix. This can be achieved by reduced curtailment time and maximization of RES hosting capacity, without compromising the operational reliability of the power system.

- General energy savings by improving operation and thus reducing network losses.
- Reduced need for ancillary services for frequency regulation and thus reduced utilization of gas-fired power generation
- Replacing fossil fuels in transport by electrification, use of hydrogen, biofuels, or other carbon-neutral fuels.
- Increasing of hosting capacity for RES.

Table 3: **Evaluation of the selected business models towards criteria**

Criteria	Power-to-Gas	Web-of-Cells	CECs
Decarbonization of the economy by increased share of RES in the generation mix.	x		
Decarbonization by maximizing of RES hosting capacity, without compromising operational reliability of the power system.	x	x	x
General energy savings by improving operation and reducing network losses.	?	x	x
Reduced need for ancillary services for frequency regulation and thus reduced utilization of gas-fired power generation.	?	x	?
Replacing fossil fuels in transport by electrification, use of hydrogen or biofuels.	x		?

In addition, it was considered the initial description of the task in the project's description of work (DoW) stipulating Citizens Energy Community as one of the models. It was also considered that several recent position papers and roadmaps point towards wider use of hydrogen decarbonization of the European economies (see [35],[36],[37],[38],[39]).

The intention is not to cover all possible variants of future plausible business models, but rather to concentrate on a representative sample allowing to uncover barriers applicable to many similar models.

3.3 Methodology: e3value in a nutshell

The selected initial business ideas have been developed and formalized as business models by applying the *e3value* methodology. This is a well-established conceptual modeling approach with an extensive documentation website ([40]), including a variety of downloadable tools and tutorials (see more details in the Annex, Section 7.1). It was initially developed at the Free University of Amsterdam in the early 2000s and has been further developed since then. *e3value* develops a formal representation of a business model to enable the analysis, map the barriers and further develop it into a business case. The methodology has been successfully applied in several R&D projects in the energy domain, such as OBELIX, BUSMOD ([41]), EcoGrid EU and SmartNet ([42]) The methodology has a dedicated website ([40]) with downloadable tools and has been also evaluated in a number of publications as [43] and [44]. Several recent publications make comparative evaluation of *e3value* with similar methodologies (see [43] and [44]).

The approach is unique because it focuses on the concept of economic value as a central modeling construct. *e3value* offers a number of interrelated core elements, also called an ontology, which are used to build a semi-formal abstract e-business model. A business model is a set of value activities and value objects, which are exchanged between these value activities. More specifically, in the electricity sector, there is a number of value activities that are common for the electricity business, namely: generation, transmission, distribution, supply, coordination of sales, etc. Actors in the electricity business are generators, distribution system operators, transmission system operators, suppliers, etc. Each actor can perform one or more of such value activities. The ultimate goal of business modeling is to evaluate the business idea and discover a business scenario feasible for every stakeholder.

A business scenario is described in terms of *e3value* modeling methodology and consists of the business model and scenario path. A business model is a set of value activities and value objects exchanged between these value activities. In the electricity sector, there is a number of value activities that are common for the electricity business, namely: generation, transmission, distribution, supply, coordination of sales, etc. Actors in the electricity business are producers, distribution system operators, transmission system operator, suppliers, etc. Each actor can perform one or more such value activities.

All the stakeholders involved in a business idea must be able to make a profit or increase their economic utility, and all of them must have a common understanding of the value proposition. Two of the main characteristics of *e3value* are that it is a graphical approach and that it focuses on the economic value. Therefore, the representation of the business idea takes the shape of a value model. A value model represents a number of actors who exchange objects of economic value with each other, i.e., it represents what objects of economic value are exchanged by whom. In fact, it represents what is offered to whom and what is requested for it in return (in the economic sense).

One of the open issues in the *e3value* methodology is how to include taxes e.g., VAT or any other charges into the value exchanges. Normally, taxes are not considered a part of value exchanges. However, in some cases when taxes or other charges become a substantial part of cash flows, they were included and further channeled to an additional actor, representing a receiver of tax-related flows i.e., the state. Some of the developed models cannot be implemented today since they require certain changes in the operational practice and in some cases even the regulatory acts, especially when it comes to the existing roles and responsibilities. Therefore, it becomes necessary to make several model-specific assumptions, which preferably can be substantiated by the official opinions of the relevant stakeholders.

Similar to the development of a use case, the creation of a business model in *e3value* includes several sequential steps, allowing a formal representation of a business idea. Following these steps allows to define specific value exchanges between the actors and corresponding scenario paths. These activities have to comply with the existing legislation, including the set of roles and responsibilities. Therefore, the stepwise process helps to uncover the limitations, potential barriers, and shortcomings limiting implementation of the business model.

3.4 Enabling factors for the business models

Several new technologies and concepts function as key enabling factors for business processes or "game changers" leading to the development and deployment of new business models. The intention of this section is to give examples of these factors, which can serve as enablers for the business models considered in our analysis. An exhaustive technical description is not in the scope of the present activity and is limited to very specific details, which are necessary for the development and assessment of a business model e.g., whether a certain process requires the introduction of heat or generates it.

Use of hydrogen

The major advantage of hydrogen as an energy carrier is that it can be produced and converted to energy with relatively high efficiency ([37]). The product can be stored and transported over long distances, while the outcome of its combustion is pure water, which can be utilized for many different purposes. For developing the corresponding business model, it was necessary to establish a general overview of the different elements of the hydrogen value chain.

Hydrogen is a key element in the ongoing sector coupling process, meaning the electrification of more areas of the economy — such as transport, buildings, and industry — by plugging them directly into the power grid or switching to green hydrogen produced from renewables (indirect electrification).

There are however several doubts related to the overall feasibility of the PTG model since the knowledge and experience, related to the construction and operation of hydrogen infrastructure, are still very limited. The following business model explores this alternative and identifies the potential barriers, which may prevent investment into the PTG infrastructure for utilizing curtailed electricity from RES.

Information and Communication Technologies (ICT)

ICT is a very broad term, which normally combines telecommunications/transmitting of information as well as its processing, by using computational power and techniques. The application of several business models requires advanced technologies for observability, optimization models and algorithms.

One of these recent technologies – peer-to-peer (P2P) decentralized concept – envisions that a consumer-centric realization of the energy transition will be accelerated by two key technological developments: digitalization and uptake of renewable energy sources. Digitalization has brought an array of ideas to develop several business cases. Digitalization has accelerated the development of smart grid concepts, which has opened up for the creation of services that enable more efficient operations of power system grids. As a result, flexibility markets and decentralized architectures have risen in prominence enabled by technologies such as:

- Internet of things, big data and analytics that accelerates automatization, artificial intelligence (AI) and machine learning.
- Distributed ledger technologies.
- Digital trading platforms
- Increased computational power

Central in P2P trading has also been the wider adoption of solar PV. P2P has been enabled by affordable solar PV as well as other distributed generation technologies. In this regard, key technologies that might accelerate P2P are electrical vehicles (EVs) and smart metering.

Decentralization of the power system

As it was already mentioned in the previous section, ICTs have contributed to rise of decentralised conceptual architecture, making it both feasible and operational. The path of development towards a more decentralized organization of the power systems nowadays is officially considered one of the probable outlooks for the future. The Ten-Year Network Development Plan 2020 (TYNDP) ([45]), which was commonly developed by ENTSO-E and ENTSO-G, considers centralization/de-centralization trends as a key driver along with decarbonization of the energy system and implement this as refers to the set-up of the energy system included centralized/decentralized innovation development paths as two alternative main scenarios for the development of the European power system towards 2040-2050.

European Technology & Innovation Platforms for Smart Networks for Energy Transition (ETIP-SNET), which brings together a multitude of stakeholders and experts from the energy sector, launched in 2018 a bold and holistic outlook for the European Power system called "Vision 2050" ([46]). The vision's main objective was defined as a fully carbon-neutral circular economy by the year 2050 in Europe. One of the main features of the vision is a close interplay or coupling between different energy carriers in the distribution network for optimal utilization of local resources. The vision is built upon an integrated Pan-European energy system with seamless operation through fully interoperable and networked sub-systems, including centrally- and locally-controlled electricity networks, supported by automated local grids.

3.5 Business Model "Production of hydrogen from curtailed electricity"

Introduction of the reference case

Generation of hydrogen from curtailed renewable electricity from wind power and PV is often mentioned as the most promising decarbonization approach. There are however several doubts related to the feasibility of this since there is no business case for this yet and everything indicates that hydrogen production would require dedicated power generation assets ([47]). The following example is an attempt to explore this alternative.

The present model is inspired by a real-life case at Varanger Kraft (Northern Norway). The company received a concession for the construction of 200 MW of wind power, but in practice cannot install more than 45 MW due to the limited hosting capacity of the existing network. Today the company prepares testing of a 2.5 MW PEM electrolyzer, which will produce hydrogen to be used domestically for transport and heating of dwellings (see [48] for details). The present case was also included into a dedicated publication (see [49]).

Assumptions, limitations, and boundaries of the model

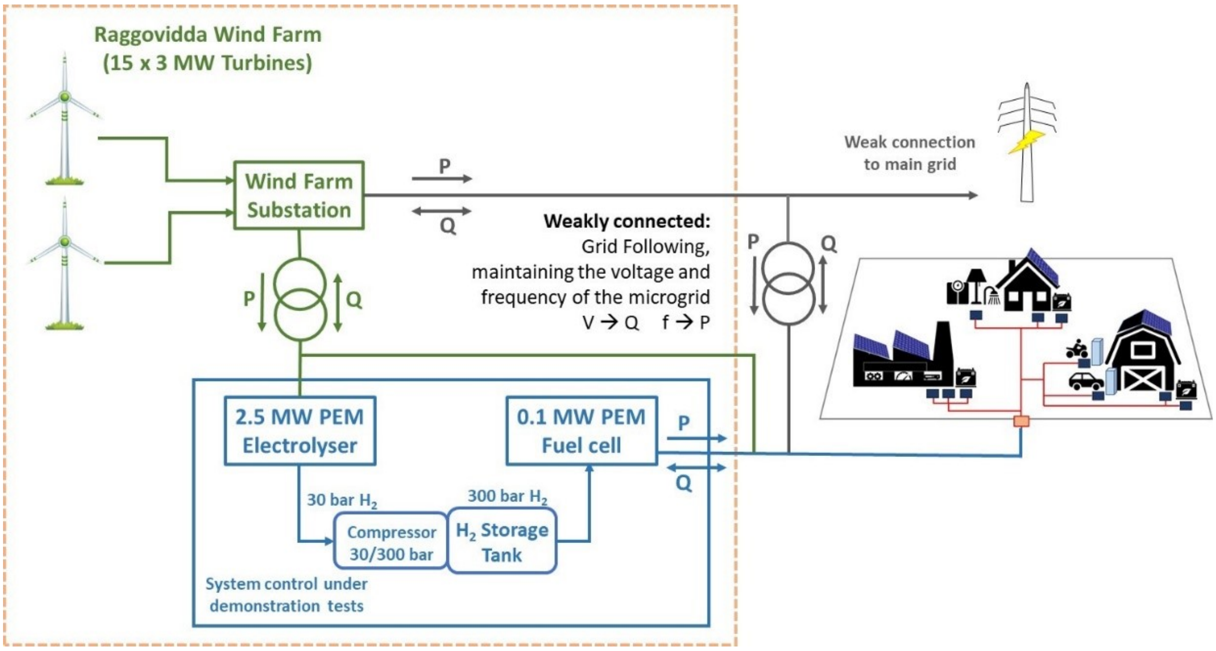

Fig. 6: **Planned deployment in Sør-Varanger, Norway. Source:**[48]

A set of assumptions has been made:

- It is assumed that the whole area is self-sufficient with energy at any time and is a net exporter of energy in form of electricity or hydrogen. This means that no external electricity generator needs to be included in the model.
- There is no local network i.e., all actors are connected to the conventional distribution network, which is used for both feeding in and consumption of electricity.
- The installation cannot function in islanded operation mode; therefore, it needs system services and frequency support. This brings the Transmission System Operator (TSO) into the model.
- Heat generated by the process and the fuel cells is not utilized in this version of the model.
- In Norway, metered data are exchanged through a dedicated date hub - Elhub, operated by the TSO - but in the business model, for the sake of simplicity, the hub is not shown.
- Assignment of responsibilities for electricity metering and billing is done according to the existing legislation in Norway.

To make the model functional it is necessary to set reasonable boundaries and make corresponding simplifications. The model does not consider local voltage management, electricity losses, or operational costs related to maintenance. In this version of the model, produced hydrogen will have unspecified export to a hydrogen buyer, who does not have any specific connections to the model otherwise.

Business idea description

Utilization of the available RES in some cases can be problematic or even impossible. The most obvious example is the utilization of wind power in remote locations, which may have rugged terrain, are sparsely populated, and do not have any substantial local consumption. Transfer of the generated electricity requires construction and continuous maintenance of the HV electricity grid, which is costly, uses substantial areas, and in general is unwanted by the public. Seasonal variations and intermittency of RES will further complicate the situation, resulting in overcapacity of the line or curtailment measures. The composition of these factors often makes utilization of the available RES impossible.

The overarching goal of the model is to maximize the utilization of the available RES resources. For the Generator the goal will be to maximize profits.

Technology selection

The model combines the following technologies:

- Wind power generation.
- Production of H2 by electrolysis (power-to-gas).
- Fuel cells for conversion of hydrogen into electricity and heat.
- H2 storage (compressed hydrogen at ambient temperature).

Actors and value activity selection

The following value activities have been identified:

- **Generation of electricity:** two different activities are presented in the model. The first is the generation of electricity by wind turbines and the second by fuel cells from hydrogen. The latter can also involve generation of heat.
- **Distribution of electricity, metering and billing:** These two activities are normally bundled under the same actor, but "Metering and Billing" can be also done by an external provider, and in some countries, this unbundling may be compulsory.
- **Generation and compression of H2:** (bundled in one single activity), H2 Storage, generation of electricity from H2 and its export. These are defined as bundled activities, which are likely to be performed by the same actor in a fairly compact area due to high safety requirements and high costs of hydrogen infrastructure, so the H2 pipeline is non-existing, and distribution of hydrogen can be neglected as an activity.
- **Electricity retail:** wholesale purchase of electricity bilaterally or through the spot market, retail of electricity to final customers.
- **Electricity consumption** is done by the final customers.
- **Buying of hydrogen:** for the sake of simplicity, buying of hydrogen is defined as a generic activity, where all excess hydrogen is channeled to.

Some of the activities were left outside for example voltage management in the distribution network, balancing done by BRPs etc.

Value interface selection

Hydrogen Agent (HA)

The HA is a new actor, who is pivotal for the deployment of this business model. The HA is responsible for the Production of Hydrogen from curtailed electricity and the following Operation of Hydrogen Storage, including compression of hydrogen. The same actor also runs Electricity Generation from hydrogen, by using fuel cells. The electricity is further sold to the Electricity Supplier and delivered physically to the DSO. In addition to this, the HA runs the Export of Hydrogen to an external Buyer of Hydrogen (BH) through a dedicated value port. The HA has two interfaces for electricity: one value port is a physical delivery of excess electricity from the EG, and the second value port is related to the exchange of electricity (purchase or sell) with the Electricity Supplier and the associated use of Electricity Distribution services and Metering. In order to ensure a reliable operation of hydrogen storage at any time, the HA purchases electricity from the ES.

Electricity Supplier (ES)

The ES is responsible for Electricity Purchase, Retail and Billing activities. For the retail: the ES has two different interfaces or value ports for retail i.e., the one towards HA as an industrial customer and the second for the regular Final Customers. For the purchase: ES purchases electricity produced by the EG, which is physically delivered to the transmission network. The ES participates in the Day-ahead market, but this is not included in the model for the sake of simplicity. The ES receives metering data from the Metering activity at the DSO. Billing as services is embedded into value exchanges showing electricity sales.

Transmission System Operation (TSO)

For the scope of the present model, the TSO runs the conventional Transmission of Electricity Distribution. For the sake of simplicity, other TSOs activities are excluded from the model.

Distribution System Operator (DSO)

DSOs main activity is the Distribution of Electricity, i.e. physical delivery of electric energy. The DSO in this model is also responsible for Metering.

Electricity Generator (EG)

The EG in this model is a local generator, supplying electricity from the Wind Power, and normally it feeds electricity into the Transmission Network of the TSO. However, due to the limited available capacity of the transmission network and in order to avoid curtailing and thus maximize the share of RES, the EG delivers the excess electricity to the HA. According to the reference case, since the Electrolyzers are located in the vicinity of generation, it delivers physical electricity directly to HA agent i.e. without the use of a distribution network as such. In monetary terms, the excess electricity is sold to the ES, which ensures economic balancing and retails the electricity to the Final Customers.

Final Customers (FC)

The FCs in the model are conventional passive end-users, buying electricity from the ES and getting it delivered physically by the DSO. The FCs are metered by the DSO and billed by the ES.

Buyer of Hydrogen (BH)

The BH buys hydrogen from the HA and sells it elsewhere outside the model's boundaries.

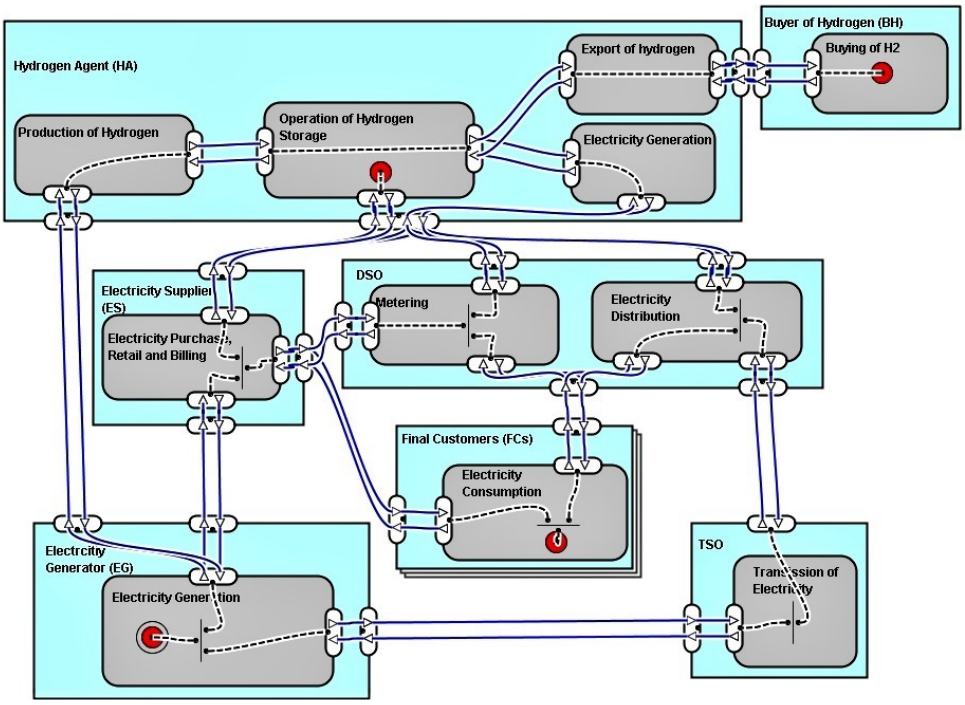

Fig. 7: **Business model "Production of hydrogen from curtailed electricity"**

The scenario path

According to the *e3value* methodology, the scenario path starts at a point indicating demand for goods or services, shown as *Start Stimulus*. In our case, the scenario starts with two actor segments showing demand for electricity and one for hydrogen:

I. FCs purchase electricity from the ES, the electricity is delivered and metered by the DSO. The DSO receives physical electricity through TSO, where it has been delivered by the EG. FCs are billed by the ES. The ES retails electricity purchased from the EG. The AND fork at the EG leads to the termination of this scenario path, the *End Stimulus*.

II. For activity Operation of Hydrogen Storage, the HA purchases the electricity necessary for maintaining reliable and safe operation from the ES, which is also delivered and metered by the DSO. The HA is billed by the ES. The DSO receives physical electricity through the transmission network from the TSO. This terminates the scenario path through AND fork at the same *End Stimulus* as the previous path.

III. The External Buyer of Hydrogen purchases compressed hydrogen from the Export of Hydrogen activity of the HA. The hydrogen was kept into Hydrogen storage. The storage received hydrogen from the Production of Hydrogen activity of HA. Electricity, necessary for the production of hydrogen was received directly from the EG (wind power). The AND fork shows that the generated electricity is delivered both to the transmission network at the TSO and for the Production of Hydrogen at HA. The AND fork terminates this scenario path at the same point as the previous two.

3.6 Business Model "Energy Community"

General provisions and guidelines

In the "Clean Energy for all Europeans" ([50]) package, the European Commission has started the formalization process of several new actors, including active customers and so-called Citizens Energy Communities (CEC) by indicating their roles and responsibilities in the IEM Directive ([51]). The intention is to provide CECs with an enabling framework, fair treatment, a level playing field, and a well-defined catalog of rights and obligations.

There are several terms describing energy communities, which are in circulation for the moment. This study refers to the official terms, defined in the European legislative acts and documents. Two formal definitions of Energy Communities were introduced in two separate Directives included in the "Clean Energy for all Europeans" package:

- The main framework for Renewable Energy Communities (RECs) was introduced by and defined in Renewable Energy Directive (RED II) [52].
- The concept of CECs was introduced in the IEM Directive [51]

Following the recent development of European legislation, these are not synonyms, and a lack of proper understanding of the terms could make communication complicated and misleading. It is important to mention that both documents had several recasts, while the most recent versions are in force. In these documents definitions of the terms are not presented in a similar manner, while some of the points are scattered in the text.

The common understanding is that RECs are a legal subset of the broader legal term CECs. Already in the opening lines of the IEM Directive, it is stated that an energy community is an effective and cost-efficient way to meet citizens' needs and expectations regarding energy sources, services, and local participation. Energy communities offer an inclusive option for all consumers to have a direct stake in producing, consuming, or sharing energy.

According to the IEM Directive and RED II Directive, an array of possible activities appears to be open for RECs and CECs (see Table 4). It is worth noticing that these documents do not grant any exclusive right to engage in activities, it rather ensures that the energy communities have the right to engage in these i.e., not prevented from doing so, and thus recognize the major

Table 4: **Definitions of Energy Communities in the European Directives. Source: [52], [51]**

Renewable Energy Community (REC)	Citizen Energy Community(CEC)
Definition of the legal entity:	
Section (16) in [52]	Section (16) in [51]
• which, in accordance with the applicable national law, is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity. • the shareholders or members of which are natural persons, small and medium-sized enterprise (SMEs) or local authorities including municipalities.	(a) is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises.

activities, which the energy communities are already doing or can do in the future.

CECs can for example undertake roles of final customers, producers, suppliers, or distribution system operators, engaging in energy generation, distribution, supply, ownership and management of batteries etc. Members or shareholders of a Citizen Energy Community do not lose their rights and obligations as household customers or active customers. CECs are subject to non-discriminatory, fair, proportionate, and transparent procedures and charges, including with respect to registration and licensing, and to transparent, non-discriminatory, and cost-reflective network charges. CECs are entitled to own, establish, purchase, or lease distribution networks and to autonomously manage them.

The Directive [51] empowers Member States to allow Citizen Energy Communities to become distribution system operators either under the general regime or as "closed distribution system operators". Once a Citizen Energy Community is granted the status of a distribution system operator, it should be treated as, and be subject to the same obligations as, a distribution system operator.

Where electricity is shared, the sharing should not affect the collection of network charges, tariffs and levies related to electricity flows. The sharing should be facilitated in accordance with the obligations and correct timeframes for balancing, metering and settlement.

Member States may decide to grant CECs the right to manage distribution networks in their area of operation and establish the relevant procedures (see [51]). It is also important to mention that the present definition of CECs presumes technology neutrality, meaning that they can be using different sources of energy, including fossil fuels.

Implementation status in Europe

The above-mentioned provisions for energy communities in the Clean Energy Package leave much room for interpretation and there is a question of how these general provisions will be transposed into national law of the member states. For the time being, there are frameworks for

***Table 5:* Possible roles and responsibilities for RECs and CECs.**

Renewable Energy Community	Citizen Energy Community
Roles and Responsibilities:	
Article 22 in [51]	Article 11 in [52]
	CECs may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders;
Article 22 in [51]	Article 16 in [52]
Member States shall ensure that renewable energy communities are entitled to: • produce, consume, store and sell renewable energy, including through renewables power purchase agreements. • share, within the renewable energy community, renewable energy that is produced by the production units owned by that renewable energy community, subject to the other requirements laid down in this Article and to maintaining the rights and obligations of the renewable energy community members as customers. • access all suitable energy markets both directly or through aggregation in a non-discriminatory manner	Member States may provide in the enabling regulatory framework that citizen energy communities: • are open to cross-border participation. • are entitled to own, establish, purchase or lease distribution networks and to autonomously manage them subject to conditions set (see the row below). • are subject to the exemptions, applied to the closed distribution systems related to procurement of energy for cover losses and none-frequency ancillary services, ownership of EV charging points, storage facilities etc. (see Art. 38 in [52]). Member States may decide to grant citizen energy communities the right to manage distribution networks in their area of operation and establish the relevant procedures. If such a right is granted, Member States shall ensure that citizen energy communities: • are entitled to conclude an agreement on the operation of their network with the relevant distribution system operator or transmission system operator to which their network is connected. • are subject to appropriate network charges at the connection points between their network and the distribution network outside the citizen energy community and that such network charges account separately for the electricity fed into the distribution network and the electricity consumed from the distribution network outside the citizen energy community.

energy communities in Germany, the Netherlands, France, and Belgium (Wallonia), which differ significantly in detail. These details, challenges and shortcomings are exhaustively described in [53].

The main features of the CEC, which are relevant to the scope of the present study are:

- Focus of renewable energy
- Collective energy self-consumption
- Local network tariffs (implemented or under evaluation)
- Sell of access production to the market

With subsidies for renewable energy in decline, energy communities are often struggling to build a business case. Local grid tariffs based on the actual network cost of the community for the public grid provide a possible avenue to create extra sources of revenues for energy communities. Several approaches for the design of fair local grid tariff models are under development ([53]), also refer to review in [54]. The main controversy is that even though the energy is consumed in proximity to its generation, the community members still need certain services from the transmission network due to the intermittent nature of the locally produced energy.

Interpretation of the European Directives may vary significantly among the European member states and making an exhaustive overview of all possible alternatives is not the intention of the present study. A relevant overview, showing the evolution of energy communities in the UK ([55]) concludes that after the support schemes such as Feed in Tariffs (FiT) are discontinued, a maturing cohort of communities are slowly becoming professional non-profit, social enterprises and in some case energy service companies, that enjoy a high level of trust, low transactions costs and self-sustaining business models. It has been also noticed that a growing number of various intermediaries, will facilitate the CECs operation and improve its economic indicators.

Assumptions, limitations, and boundaries of the model

Considering that the framework of both CECs and RECs is still under development, the present study will consider Energy Community as the main term. It is also assumed that:

- The Energy Community has a local generation capacity operated by active customer (-s), which are feeding electricity into the distribution network
- The physical connection of the Energy Community and its legal terms are sufficient to sell electricity outside its boundaries, at least at some periods of time, so the surplus power is not curtailed but exported.
- The local generation at active customers does not cover the ECO's needs for electricity during the whole year, e.g., due to seasonal generation patterns for the installed PV or small-scale hydropower.

Business idea description

The present version of Energy Community is fairly conservative and presumes first of all common ownership and governing allowing the members to pull together resources (both financial, labor, and ownership rights) necessary for the development of the locally available renewable energy resources. The generation asset will be fully or partially owned and governed by the Energy Community; the specific form of organization may vary.

The conservative version also presumes a rather "passive" local DSO, which reduces or postpones its investments into expansion and maintenance of the existing network connection, which may be necessary to accommodate generation from the RES or possible growth of the consumption. The DSO does not have to make any active involvement and control into the community operation

Goal selection

The main goal for the members of the energy community is to increase the share of RES in their consumption and reduce electricity costs plus some of the network tariffs related to energy.

Technology Selection

In general, energy communities are considered to be technology-neutral. The present business model involves active customers without the specification of generation technology. For the operation of the internal energy market, the model uses P2P trade or similar.

Actors and the value activities selection

Generation of (usually renewable) energy is often the primary activity of energy communities. It is also important to mention that the present definition of CECs presumes technology neutrality, meaning that they can be using different sources of energy, including fossil fuels.

Independent Community Agent (ICA): The necessity of establishing this new role has been pointed out in several publications in order to increase the overall feasibility requirements for the community. This actor runs two main activities:

- **Operation of a local electricity market** for continuous trading between the members of the Energy Community. It can be a P2P market or anything else with similar functionality.
- **Metering and billing** service also done by the ICA in order to support the local trading activity and its settlement

These two activities have two different value ports since they are not bundled.

Active Customers (ACs): This role is essentially based on the definition provided by [51]. **Consumption and generation of electricity** are depicted as a single combined activity, done by ACs. It has been decided to combine these since the ACs normally use one single interface and net electricity metering. Following the definition, the ACs may operate energy storage if necessary.

Consumers (COs): This role is related to the consumption of electricity and does not differ very much from conventional end-users of electricity.

Transmission System Operation (TSO): For the scope of the present model, the TSO runs a conventional activity i.e., Transmission of Electricity.

Distribution System Operator (DSO): DSOs main activity is the Distribution of Electricity, delivering electric energy from the Transmission Network to the Energy Community. Export of excess self-generated electricity from the Energy Community to the grid is possible. In this model, Metering and Billing as an activity is transferred to the ICA. DSO operates the distribution network and charges ICA for this service.

Electricity Supplier: ES is responsible for Electricity Retail activity dealing with wholesale purchase, portfolio optimization and retail of electricity to the consumers. In the Energy Community, the ICA purchases electricity on behalf of the community's members. The ES participates in the Day-Ahead market, but the latter is not included in the model for the sake of simplicity.

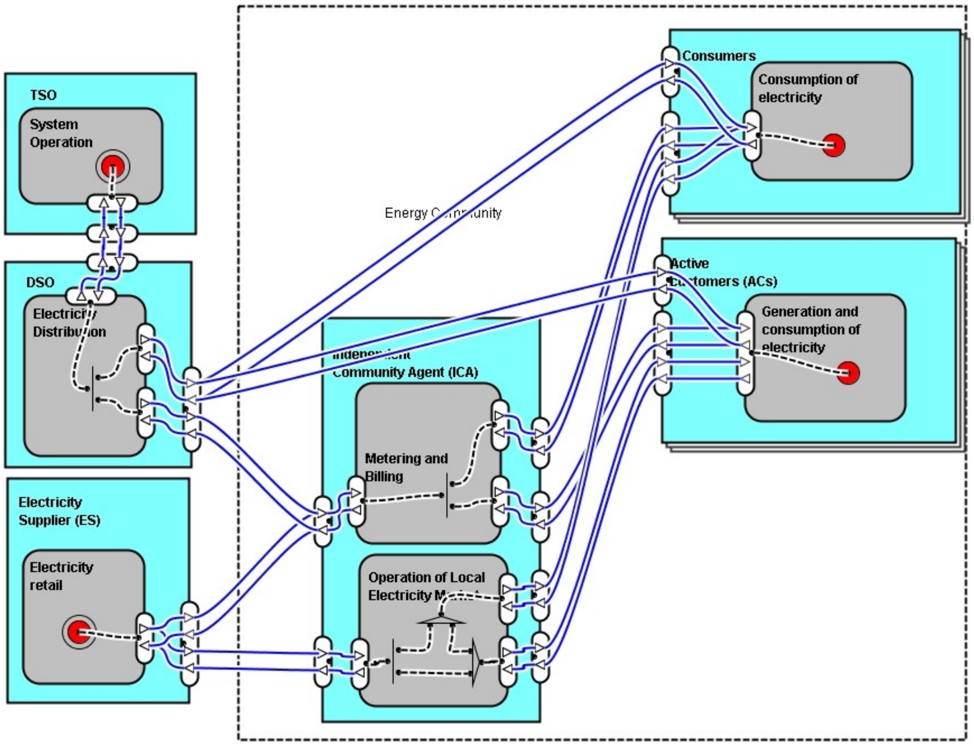

Fig. 8: **Business Model "Energy Community"**

The model does mention specifically congestions management in the distribution network, mostly because WoC as a concept is expected to reduce the need for it.

Description of the business model: the Scenario path

In this model, there are two actors, who show demand for electricity and therefore initiate two scenario paths: Consumers and ACs. These scenario paths can act simultaneously.

Consumers purchase electricity through the Local Electricity market, which is operated by the ICA (see examples in [54, 56]. The electricity can be generated locally by the ACs or sold from ES. The ICA provides metering and billing services to the Consumers and delivers data to both DSO and ES.

The ACs may consume electricity from their own generation or in case it is not sufficient, they purchase electricity from the Local Electricity Market, operated by ICA. If the ACs have excess electricity generation, the output is delivered to the Local Electricity Market and can be traded to the Consumers in the Energy Community. In case the generation is higher than the demand in the Energy Community, the excess output will be sold outside via the ES. The ICA provides bidirectional metering and billing services to the ACs. The value exchanges for ACs happen through two different ports, in the same manner as for the Consumers, because the same physical interfaces are used for both the sale and purchase of electricity.

The ICA operates the Local Electricity market, which offers several alternative flows for the scenario path, which is indicated by logical switches OR and FORK:

- The Consumers can purchase electricity from the ACs or the ES.
- The ACs can sell electricity to the Consumers or (in case the generation exceeds the overall consumption) to the ES.
- The ES serves both Consumers and ACs.

The logical representation of the Local electricity market is somewhat simplified, since showing the whole range of alternatives is not the main focus here. The ES serves a bidirectional energy flow (sale/purchase) of electricity from the ICA and receives the metered data. DSO in this model provides physical exchange of electricity between the actors and charges the grid tariff for delivery and feeding to the Consumers and ACs. The DSO receives metered data for the community from ICA, which has overtaken this activity.

3.7 Business Model "Web-of-Cells"

Web-of-Cells (WoC) are defined as a portion of the power grid able to maintain an agreed power exchange at its boundaries by using the internal flexibility of any type available from flexible generators/loads and/or storage systems The initial development of the WoC concept in the FP7 ELECTRA IRP project ([57]) had a specific functional focus, trying to find whether the architecture was viable from the technical point of view, while there are still several open questions in the business layer. In addition, several developments have happened during recent years, especially when it comes to the introduction of new entities as ACs and Citizens Energy Communities and in general the system of systems approach. These make WoC a much more relevant concept today.

Introduction

The FP7 project ELECTRA IRP ([58]) developed a decentralized architecture for the future power system coined WoCs and a corresponding set of novel controls for balancing and voltage regulation. The Cell is a portion of the power grid able to maintain an agreed power exchange at its boundaries by using the internal flexibility of any type available from flexible generators/loads and/or storage systems. The total amount of internal flexibility in each cell shall be at least enough to compensate for the cell generation and load uncertainties in normal operation ([57]). The Cell is not a microgrid and does not have to be energy self-sufficient or able to operate in islanded mode.

The idea behind the WoC is that the growing share of renewables in the distribution network will create challenges for the conventional centrally-operated power system, generating imbalances and congestion on different voltage levels. The presence of multiple cells or complete transfer to the cell-based operation will reduce uncertainties on the system level by reducing both imbalances and congestions and thus reducing the necessity for the ancillary services provided by the system operator. Solving local problems locally will also prevent the propagation of imbalances and congestion at the transmission level. The main advantage of the WoC architecture is a substantial increase in hosting capacity for renewables, without compromising the overall reliability of the grid.

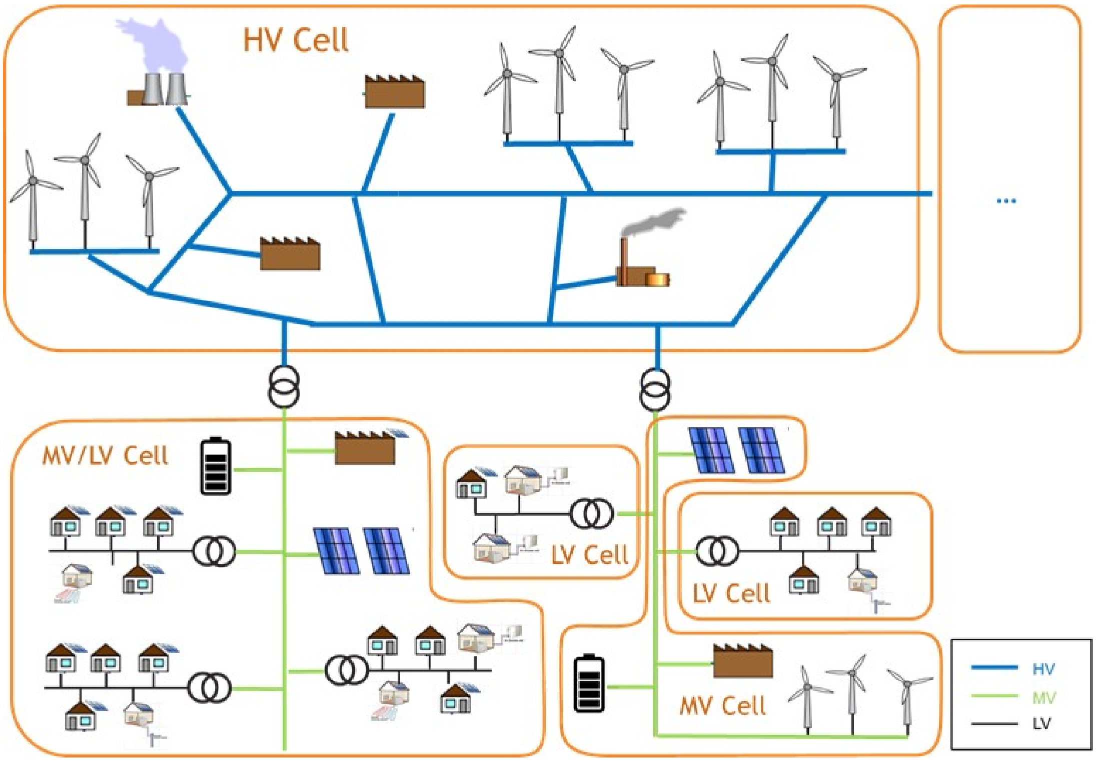

Fig. 9: WoCs concept. Source: [57]

Ability to maintain an agreed power exchange or even adjust it opens possibilities for a Cell to act as a provider of services to the system operator. It is necessary to mention that the concept has been developed and validated mostly from the technical point of view ([59]) When it comes to the legal status and corresponding roles and responsibilities, several assumptions have to be made. Following the definitions, for the WoCs, it is critical that the WoC Operator has balancing responsibility for the corresponding Cell. WoC does not require shared ownership and any specific limitations related to its size.

Assumptions, limitations, and boundaries of the model

Implementation of the WoC concept requires the following modification of the established roles and responsibilities:

- Formalizing of a new business actor – the WoC Operator (WCO), responsible for the local balancing of the Cell. It is assumed that the WCO is a natural monopoly and therefore is subject to the regulation of its business activities.
- In the present version of the business model the WCO covers two additional activities – running the Cell's distribution grid and metering and billing.
- Roles and responsibilities for the ACs are based on the latest recast of the IEM Directive.
- A market for the trading of the control resources (MCR) necessary for the operation of the Cell, including balance control and voltage regulation becomes necessary. The market is operated by the Independent Market Operator (IMO)

- For the sake of simplicity, the MCR does not trade any surplus reserves towards the TSO i.e., the bidding happens within the Cell and the WoC Operator is the only purchaser

As it was mentioned before, the Cell is not a Microgrid and functions as a consistent part of the power system. This presumes that the Cell is still involved in the existing markets as Day-ahead and Intraday and actors as TSO and ES.

Business idea description

The main business idea for WoC is to optimize the system operation by reducing the need for centrally-dispatched ancillary services and thereby increasing hosting capacity for RES in the distribution grid without compromising the overall reliability of the grid's operation.

Goal selection

The main goal for the model is to meet the predefined power exchange on the cell's tie-line (-s) by using the existing flexibility in both generation and consumption

Technology selection

Implementation of the WoC concept requires the introduction of new types of controls for balancing and voltage regulation. For the purpose of this paper, it is not however necessary to describe this in detail, since this is explained in detail in [59].
It is also presumed that a Cell may include generation, based on RES technologies as PV or/wind power having an intermittent nature.

Actors and the value activity selection

WoC Operator (WCO): The WCO is entirely a new role, which was initially launched in the framework of WoC concept by ELECTRA IRP project. Three activities are done by the WCO:

- **Cell System Operation**, running a set of control schemes, necessary for the operation of the Cell. For this purpose.
- **Cell Electricity Distribution** is depicted as a separate activity, similar to the regular operation of distribution network today, which is defined as a natural monopoly and is regulated accordingly.
- **Metering and Billing** is also defined as a separate activity, and also can be similar to today's practice in distribution networks.

Independent Market Operator: A MCR necessary for the operation of the Cell, including balance control and voltage regulation becomes necessary. The market is operated by the IMO. The IMO runs Market Operation activities dealing with the trading of resources, required for the operation of the Cell. The issue of trading resources for ancillary services at the distribution level has been explored in several projects, for instance, H2020 project SmartNet ([60]), where different alternatives were evaluated. Based on this, the present study suggests an independent market operator or a single market platform hosting trade, where bids are connected to certain locations i.e., Cells.

Local Generator (LG): Depending upon the local conditions e.g. availability, the Generation of Electricity can be also an optional activity within the Cell, done by an LG. A Cell however does not have to be self-sufficient in terms of electricity generation and the Cell's consumers may purchase electricity from an external ES.

Electricity Supplier: ES is responsible for Electricity Retail activity dealing with wholesale purchase, portfolio optimization, and retail of electricity to the Cell's consumers. The ES participates in the Day-ahead market, but the latter is not included in the model for the sake of simplicity.

Active Customer (-s): Consumption and Generation of electricity are depicted as a single combined activity, done by ACs. It has been decided to combine these since the ACs normally use one single interface and net electricity metering.

Consumers (COs): Electricity Consumption is a conventional activity in the Customers' segment.

Transmission System Operation (TSO): For the scope of the present model TSO runs two activities i.e., conventional Transmission of Electricity and a new activity required for the operation of WoC – System Operation, which refers to the calculation and definition of setpoints on physical WoC interface (see [43] for details).

Distribution System Operator (DSO): DSOs main activity is the Distribution of Electricity, delivering electric energy from the Transmission Network to the Cell. Export of excess self-generated electricity from the Cell to the grid is possible, but not a foreseen primary activity for the Cell and therefore is omitted from the study. There is an additional value exchange connection between the TSO and DSO, providing setpoints defined for the Cell since this is necessary for WoC operation. Also refer to related and emerging literature in [61]

The model does mention specifically congestions management in the distribution network, mostly because WoC as a concept is expected to reduce the need for it.

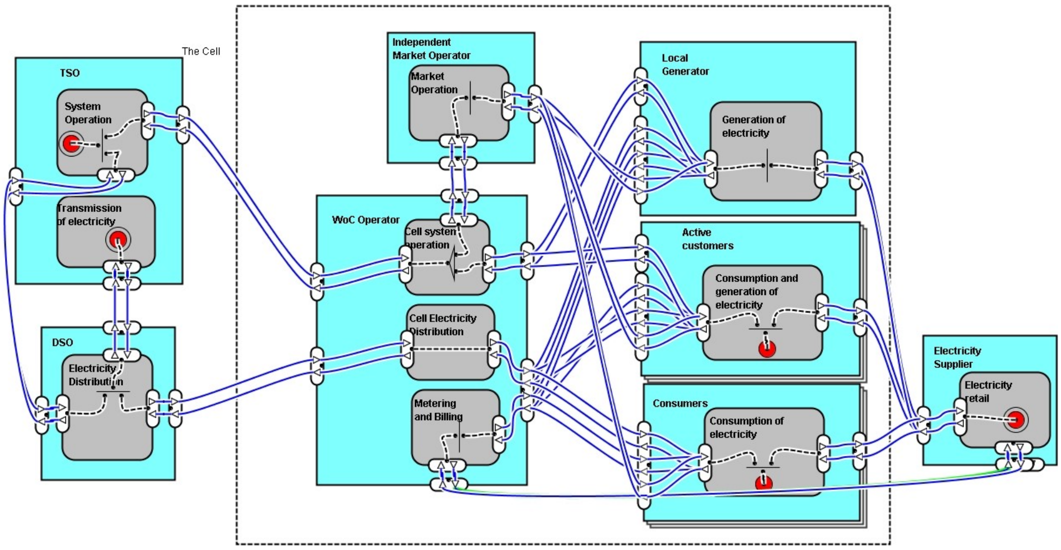

Fig. 10: **Business model for WoCs**

The Scenario path

The analysis of this scenario can be done following Figure 10. In our case, the scenario starts at two actor segments showing demand for electricity: ACs and COs, which have contractual agreements for electricity supply with the ES. This terminates the first scenario pant at ES.

The same demand through a AND fork at both ACs and COs goes towards three separate activities at WoC, covering (bottom-up) "Metering and Billing", "Cell Electricity Distribution" and "Cell System Operation". The latter is essential for the functioning of WoC as a concept and combines a set of controls, specific for WoC. Following the scenario path, resources for running these controls are procured from the IMO, which provides trading services to LG, AC and COs.

On the left-hand side of the model, the WoC Operator (WCO) procures Electricity Distribution services i.e. physical delivery of electricity from the DSO and calculation of operational setpoints from the TSOs System Operation activity (ending of the path at *End Stimulus*). The DSO procures transmission services i.e. physical delivery of electricity from the corresponding activity at TSO (ending of the path at *End Stimulus*).

3.8 Mapping of barriers and investment determinants

Following the *e3value* methodology in the development of business models helps to uncover several underlying challenges and shortcomings, which may create critical issues in the actual implementation of the intended business ideas and later compromise their sustainability.

The section presents indications and concerns, which were noticed during the development of the business models.

- Assignment of roles and activities to specific actors

- Bundling of activities, provided by the same actor
- Definition of value exchanges between different activities and corresponding actors

Since the limited time and scope of the present task do not allow to make an exhaustive study, these issues were further verified by searching whether these issues have been raised before.

Regulation and new business models

Very little information about a formal framework for the development of regulatory conditions, supporting new concepts and business models is available. One can assume that the process includes four sequential steps:

- Understanding the context and needs for a concept
- Intentions for the introduction of a concept
- Main details defined, ongoing development
- Regulation becomes well-defined and enforced

Mapping the three developed business models towards these steps is presented in Figure 11.

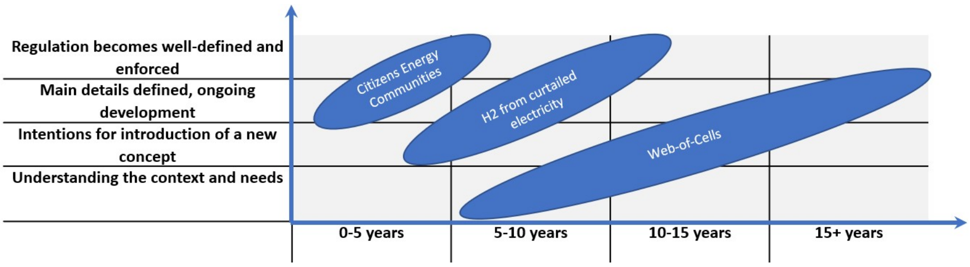

Fig. 11: **Introduction of regulation for the selected business models**

The next sections introduce the barriers, which were identified for each of the developed business models.

3.8.1 Barriers for business model: "Production of hydrogen from curtailed electricity"

These barriers are related to the specific business model related to the generation of hydrogen from curtailed electricity in remote locations. Documents from the most recent meeting in the European Forum of Gas Regulators (the Madrid Forum) indicate that there are still many open questions related to the regulation of hydrogen infrastructure ([62]). The present study specifically focuses on the three most important barriers, which are apparent from the developed business model.

Regulatory Status of PTG Facilities: Roles, Responsibilities and Ownership

The immediate issue, which was noticed during the development of the business model, was the necessity to establish a new business role – the HA, having a very complex nature due to combining several business activities and linking together hydrogen and electricity. In the reference project, this role was actually assigned to a newly established company within the Varanger Kraft concern.
The main challenge is that responsibilities for this new role are still very unclear, especially when it comes to ownership and operation of the following:

- PTG facilities as electrolyzers
- Supporting facilities such as compressor stations and pipelines
- Other supporting facilities such as hydrogen storage
- Any peripherals for the retail of hydrogen (e.g., vehicle charging stations and export terminals)

In the power industry, there is a very clear picture of roles and responsibilities for the main actors, including limitations such as, for example, ownership and operation of energy storage ([51]). The picture is not static, but modifications happen in well-structured public discussions/consultations and are formalized in different regulatory acts.

When it comes to hydrogen, several issues remain unclear. Further investigation shows that, for the time being, the European Forum of Gas Regulators (the Madrid Forum) still considers two variants:

- PTG as "conversion service", not energy production, and thus can be considered as a natural monopoly
- PTG as a commercial activity, which cannot be done by regulated parties

The difference between a regulated natural monopoly and commercial activity is essential when it comes to investment decisions since it defines future revenues. This issue was pointed out by the WindEurope association, which is one of the key RES stakeholders in Europe ([63]).

Third Party Access to hydrogen infrastructure

In addition to the ownership and operation of electrolyzers, there are several interlinked issues including Third Party Access (TPA) to pipelines and storage facilities from possible competing producers and suppliers of hydrogen. The introduction of TPA and its type (negotiated vs. regulated) is essential for both recovering the initial investments into the pipeline networks as well as the development of a competing hydrogen-producing infrastructure i.e., electrolyzers.

Cross-sectoral involvement of actors

The above-mentioned issue has an additional dimension, related to sector coupling: it is unclear whether TSOs and DSOs can involve themselves in hydrogen production, transportation and storage or not. It is natural to draw parallels to the existing regulation of Electricity System Operators' involvement into ownership and operation of energy storage ([51]), where despite the limitations, considerable exemptions can be still granted to System Operators.

Origins of hydrogen: is it really green?

This issue has previously been raised by WindEurope (see [63]). The introduction of an electrolyzer will inevitably bring the necessity of its optimal operation and utilization of the electrolyzers' capacity, which can be obviously improved by using electricity from the conventional grid when there is no wind generation available. Since the conventional grid may have different energy mixes, this raises the question of whether the produced hydrogen is carbon-free or not. This is especially relevant in case any RES-supporting schemes are applied to a certain PTG unit.

Table 6: **Summary of barriers for business model "Generation of hydrogen from curtailed electricity"**

Title	Description	Importance	Consequences for investment
Regulatory status of PTG facilities (electrolysers)	Undefined status for H2 electrolysers: natural monopolies vs commercial activities	Uncertain future revenues from electrolysers	This will limit and delay the initial investment
TPA to H2 infrastructure	TPA for PTG facilities (pipelines) has not been introduced yet	TPA will reduce entry barriers for PTG actors and increase the competition.	TPA may result in competitive H2 prices and reduced rate of return on infrastructure investments
Cross-sector involvement of actors	It is unclear whether electricity SOs can own and operate PTG assets	Unclear (for the time being)	Possible cross-subsidising
Tracing the origin of produced H2	No methods for proving origins of H2 produced by electricity from the grid with varied energy mix	The issue influences eligibility of support schemes including taxation.	Reduced returns / longer investment payback period

3.8.2 Barriers for business model: "Energy Community"

The Commission started the formalization of CECs in its recent Directive ([51]) by introducing general definitions, terms, and responsibilities for CECs. These are however intentionally generic, allowing the member states to explore various options for the development of CECs before they can be established as a permanent actor within the power sector. Within the BRIDGE initiative, a comprehensive overview was prepared, summarising the present status for implementation of the CECs in Europe, challenges and shortcomings ([53]), which is not necessary to repeat in the present report. The development of the business model has pointed out several barriers.

Energy Community and Transmission Network

One of the main questions, which was uncovered, is how the use of system services provided by the transmission network should be reflected in the grid tariffs, paid by the members of the community. There is a common opinion that CECs are not using the transmission network and thus can be exempted from paying for the services. In fact, this is not entirely correct, since at least frequency support requires services from a TSO. It appears that CECs will be operating on tiny profitability margins, where any substantial network charges will be important.

Energy Community and Distribution Network

The IEM Directive envisions an array of activities, where CEC can engage ([51]), including generation, including from renewable sources, distribution (including ownership or leasing), supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders. In addition, it is explicitly mentioned that members of a CEC do not lose their rights and obligations as household customers or ACs. This creates uncertainty in the definition of distribution network tariffs for members of the community. In addition, it potentially opens contradictions between activities, which are normally considered natural monopolies and competitive ones.

***Table 7:* Summary of barriers for business model "Energy Community"**

Title	Description	Importance	Consequences for investment
CEC and Transmission Network	It is unclear to what extent a CEC uses services from Transmission and what should be the grid charges.	Feasibility of CEC depends upon the level of grid charges.	Introduction of full-scale charges will diminish any potential benefits for member of CEC. Reduced investment incentives into RES under CEC.
CEC and Distribution Network	The present regulations allow multiple and potentially contradictive activities for CECs.	This creates an uncertainty in definition of distribution network tariffs for members of the community. This may create contradictions between activities, which are normally considered as natural monopolies and competitive ones.	Introduction of full-scale charges will diminish any potential benefits for member of CEC. Uncertainties, investment delays.
Roles and responsibilities of Independent Community Agent	Implementation of this business model depends upon formalisation of a new actor, which will carry our several roles and responsibilities e.g. operation of local market, metering and billing.	There are several roles, which have to be taken in order secure operation of Energy Communities.	Uncertainties, investment delays.
Roles and responsibilities of Independent Community Agent	Implementation of this business model depends upon formalisation of a new actor, which will carry our several roles and responsibilities e.g. operation of local market, metering and billing.	There are several roles, which have to be taken in order secure operation of Energy Communities.	

3.8.3 Barriers for business model: "Web-of-Cells"

The WoC as a concept is relatively new and still has a long way to go before becoming operational. As it was shown in the business model, the introduction of WoC can happen gradually, especially in areas, where it is feasible i.e., with a substantial share of renewable generation, which must be managed on the cell level, as well as sufficient flexibility on the consumption side allowing this. The concept is still under development, meaning that there is a lot of uncertainty about its details. Therefore, only the critical barriers will be mentioned below.

Delegation of balancing responsibility

The pivotal difference, making WoC operational at all, is granting responsibility for local balancing and associated controls to a Cell. For the time being, this is an exclusive legal responsibility for TSOs stipulated in the European regulation, even though there are certain opinions that TSOs should share it with DSOs. In WoC each Cell is responsible for maintaining the predefined power flows and voltages on its interfaces. This barrier is a prohibitive issue for the implementation of WoCs even at a limited scale.

The Cell Operator: roles and responsibilities

Already from the beginning of the WoC concept, one necessary role was defined – The Cell Operator, since the Cell has to be operated by someone. The Cell Operator may run multiple Cells or even can be automated, at least for a regular operation. There are however several questions, related to ownership and operation of the Cells' assets – the local grid, metering devices, storage, EV chargers, and any required power electronics.

Local Market Operator

Operation of WoC also requires a possibility for the trading of resources, necessary for running the local controls such as balancing and voltage regulation. This is obviously a gap, but not critical.

***Table 8:* Summary of barriers for business model "Web-of-Cells"**

Title	Description	Importance	Consequences for investment
Delegation of balancing responsibility	Introduction of the concept presumes that a Cell is responsible for maintaining a pre-defined power exchange on it interfaces.	This is compulsory for creation of the concept	This is prohibitive issue for the investment
Roles and responsibilities for the WoC Operator	Definition of specific responsibilities e.g., local balance and voltage control and any limitations related to ownership.	Several open issues related to ownership and operation of the Cells' assets – the local grid, metering devices, storage, EV chargers and any required power electronics.	Uncertainty, delaying investments
Local Market Operator	Operation of WoC also requires a possibility for trading of resources, necessary for running the local controls as balancing and voltage regulation.	This is compulsory for creation of the concept	This is a prohibitive issue for the investment

4 Welfare distribution dimension

The third dimension that needs to be considered when trying to identify investment determinants and barriers is the welfare distribution dimension. As mentioned before, within openENTRANCE, four different decarbonization pathways have been developed and modeled in the open energy system modeling framework GENeSYS-MOD, see Figure 2. Different aspects of the transition pathways are studied in detail in a variety of case studies in the project. In this chapter the pathways are assessed with focus on distributional effects. GENeSYS-MOD and many of the other modeling frameworks used, aim at system cost minimization and provide one first-best solution, which is not necessarily an optimal solution for each group of actors seen individually. In order to assure that the developed pathways are policy-relevant, there is a need to better understand what they mean for different sets of actors in comparison to others. If certain developments in the pathway result in any actor coming out with an absolute or perceived welfare loss in contrast to others, this might make the envisaged path more unlikely to be able to be implemented in practice.

Here, the welfare distribution dimension has been analyzed from three different perspectives: the country perspective, the technology perspective, and the consumer perspective. In the last decade, the understanding of the importance of ensuring that the transiting has to be fair has grown rapidly. The concept has gained public acceptance and a whole new research and project body, using a wide range of different methods to explore this topic, has been established.

The approach taken in this chapter focuses on generating more general insights, which can be drawn from already existing modeling results by the project's main energy system model as well as the pathway assumptions and other available, statistical data on country and consumer level. This task was conducted on the first round of results on the Pan-European pathways in 2021 (openENTRANCE Deliverable D3.1 [26]). This iteration of results was not yet optimized on a country input data level and this analysis has also contributed to improving the results generated for the final version of the project's pathway results.

4.1 Country perspective

In the European decision-making processes, individual country interests are at the core of many debates and need to be addressed sufficiently if major changes affecting the overall European energy system are to be achieved. Hence, in order to get a better understanding of which potential barriers could arise for any of the different decarbonization pathways, the results obtained by GENeSYS-MOD were analyzed from a country-level perspective. The energy system modeling framework GENeSYS-MOD optimizes for total, meaning European, system costs and does not consider distributional effects between different European countries.

When comparing the burden assignment between countries, a variety of different aspects can be considered. Given the nature of the results generated by the modeling framework used, we have focused on the following aspects: The different starting situations regarding power production, the shift/decarbonization of the electricity system with power system production capacity increase, and the trade balances of energy commodities on a country-level.

Fossil fuel share in the current power system

The electricity systems of the 30 countries/regions analyzed differ substantially today, regarding the share of renewables already in the system and the share of fossil-fuel-based electricity production that needs to be phased out/replaced in order to reach the target of a decarbonized system by either 2040 for the 1.5 degree scenarios or 2050 for the 2 degree compatible scenario.

***Table 9:* Share of power production capacity installed in 2015 that is fossil-fuel based.**

Region	**AT**	**BE**	**BG**	**CH**	**CZ**	**DE**	**DK**	**EE**	**ES**	**FI**	**FR**	**GR**	**HR**	**HU**	**IE**
2015	27%	42%	44%	5%	55%	24%	32%	95%	43%	49%	15%	54%	41%	66%	66%
Region	**IT**	LT	LU	**LV**	**NL**	**NO**	**Balkan**	**PL**	**PT**	**RO**	**SE**	**SI**	**SK**	**TR**	**UK**
2015	55%	51%	27%	38%	78%	3%	46%	74%	24%	37%	11%	38%	33%	51%	69%

Table 9 shows the share of fossil-fuel-based power production capacity of each of the countries/regions for the base year 2015. While Norway, Switzerland, and Sweden's electricity systems are already almost fossil-free, countries like Poland, the Netherlands, and Estonia are heavily dependent on fossil fuels for their electricity production. Norway, Switzerland, and Sweden hence do not need to make major changes in the existing power system but rather need to ensure that they increase renewable production to handle future electricity demand increases. Sweden and Norway also find themselves in a good position when considering the energy mix for residential heating. Both countries use little fossil fuels, Norway's heating system being heavily electrified and Sweden's relying heavily on biomass. Switzerland, however, uses mainly boilers to provide residential heat and those are, to a large extent, fueled by oil or gas.

The effort that needs to be undertaken to decarbonize the existing power system is greatest for Poland, the Netherlands, and Estonia. However, the three countries' challenge to achieve this differs heavily. The Netherlands are a high-income country with a highly educated workforce and rely mainly on gas. Gas resources (due to their lower carbon emission factors) are/can be phased out at a slower pace compared to other fossil fuels. This allows for more time for this task. With costs associated with the deployment of renewable power generation, and enabling technologies such as hydrogen, expected to further decrease in the future, this softens the burden for this country. Also, an already skilled workforce can facilitate the change to a more complex and "high-tech" renewable electricity production system. The pathways suggest the installation of large amounts of both offshore wind power and utility-scale photovoltaic, for which skilled personnel is crucial.

Poland relies mainly on coal to power its electricity system. It is also Europe's largest coal producer ([64]) and accounted in 2021 for more than 40% of all coal consumption in Europe alone ([65]). This implies an even greater challenge to decarbonize the electricity system. Not only do almost all existing power production capacities need to be changed but they are also currently using domestically produced fuels, hence the change will result in a major decrease in coal demand and affect the domestic labor market strongly. The pathways suggest replacing coal with gas in the near future, combined with large-scale renewable production capacity deployment. Although this makes sense from an emission-reduction perspective, given this year's developments and the resulting gas shortages in Europe, decarbonizing a country's energy system by increasing its dependency on foreign gas is not a popular option anymore. These developments drive the need for an even faster change to more renewable production. This, however, might face the barrier of not enough qualified workers being available, who are needed to build, maintain, and run these more complex installations.

Estonia's electricity system is the most fossil-dependent in 2015 - in installed power production capacity - of all European countries/regions in our dataset. The country's energy system is heavily relying on domestic shale oil, making it one of the most carbon-intensive in the world.

The share of shale oil in electricity production has dropped significantly in the last 10 years, but this has resulted in larger dependencies on coal, which is also highly carbon-intensive. Although the task of decarbonization for Estonia is massive, the country is in the privileged situation of being a net exporter of electricity, which from a purely national perspective of energy security, opens up the possibility to shrink the production capacity and by this comply with emission reduction targets in the short term.

Power production capacity increase

A further important aspect for the country-level feasibility of the pathways is the modeled increase in installed power production capacity, i.e. the new power capacity that needs to be built/added within the next 30 years. While it is expected that all countries have to increase their installed capacity within the power sector to address the needed electrification to meet the decarbonization targets, the total, as well as the relative amount compared to what is installed today differs widely between countries. Table 10 shows the installed power capacities in GW in 2015 and the scenario-specific increase in production capacity by 2050 per country. Please refer to the openENTRANCE Deliverable D7.1 [66] for a qualitative description of the different scenarios.

***Table 10:* Installed capacity of 30 countries' power production in GW and relative increase in installed capacity by 2050 for the four openENTRANCE scenarios. TF - Techno-Friendly, GD - Gradual Development, SC - Societal Commitment, DT - Directed Transition.**

Region	**AT**	**BE**	**BG**	**CH**	**CZ**	**DE**	**DK**	**EE**	**ES**	**FI**	**FR**	**GR**	**HR**	**HU**	**IE**
2015	26,3	22,4	13,4	20,1	21,1	156,2	12,3	9,9	100,9	17,7	120,8	19,4	4,9	8,0	9,8
TF	2,0	2,4	1,6	1,9	1,5	2,6	4,8	0,5	4,3	2,4	2,7	3,8	3,2	3,4	3,6
GD	2,6	3,0	2,2	2,0	2,1	3,4	8,3	0,6	4,4	3,6	3,8	6,5	3,2	5,5	7,6
SC	3,1	3,0	4,1	2,3	3,2	4,1	3,7	0,9	6,4	3,7	4,2	7,9	2,8	11,2	3,4
DT	2,6	3,6	2,1	2,1	2,0	3,1	5,0	0,8	4,1	3,3	3,0	5,5	3,7	6,0	5,3

Region	**IT**	**LT**	**LU**	**LV**	**NL**	**NO**	**Balkan**	**PL**	**PT**	**RO**	**SE**	**SI**	**SK**	**TR**	**UK**
2015	124,3	3,4	2,0	3,0	34,3	35,9	20,0	39,8	28.6	21.9	42.1	3.7	7.6	73.7	72.2
TF	1.5	3.4	2,5	3,8	2,2	1,5	3,7	3,2	2,5	2,8	2,0	1,7	2,7	6,3	4,2
GD	2,1	5,4	3,5	6,7	3,5	1,6	8,8	6,2	3,4	4,1	2,7	2,5	3,7	8,8	6,6
SC	2,4	4,5	3,4	4,5	3,6	1,7	4,8	6,2	4,0	5,6	2,9	2,3	3,8	7,0	6,7
DT	2,2	4,3	3,5	5,9	3,7	1,5	5,2	4,9	2,7	4,0	2,5	2,5	3,6	6,3	5,1

Modeling results obtained by GENeSYS-MOD show an increase in production capacity needs for all but one country/region, namely Estonia. In terms of the share size of the already installed production capacities, Norway, Switzerland, Czechia, Sweden, Bulgaria, and Italy need to increase capacity the least. This still means an increase of between 50% and a doubling. Countries like Spain, the Balkan region, the UK, and Turkey show the highest relative increase. Given that these countries have large production capacities already in the starting year, the absolute increase, especially in Turkey will be enormous. The reasoning behind these very large increases is in many cases the large availability of space for renewable installations and good renewable potentials combined in these countries. Turkey for example shows a threefold increase in its total power production capacity by 2025. However, especially some countries in the Balkan region as well as Turkey have been facing considerable economic challenges in the last years, which might result in making large foreign investments into renewable projects in these countries less attractive, as the technical circumstances would suggest. This potential barrier could result in more renewable development needs in other countries. Also, Greece and Hungary face the situation of having to increase installed capacity manifold; both are countries that are still facing challenges on the international financial market, and hence might have difficulties accessing enough financial capital and attracting enough foreign investment to achieve this.

Trade balances and international dependencies
Large import dependencies for countries or any specific group of countries can be a major barrier to reaching the desired decarbonized system. Given the geopolitical developments so far in 2022, import dependencies have been shown to put Western economies in real risk. A more general opportunity that the scenarios hold, is their quick decrease in coal use. Europe is highly dependent on imports of hard coal (almost 60% in 2020 - [67]), hence decreasing that dependency is an opportunity to achieve more energy security in Europe. In the scenarios analyzed, natural gas plays a crucial role in the shift to a decarbonized system, due to its lower carbon intensity compared to coal and oil.

For Poland, which in the reference year is mainly dependent on domestically sourced coal, the scenario pathways suggest a switch to less emission-intensive natural gas as the main resource. However, this would put Poland into high import dependencies, not only vulnerable to geopolitical tensions but also large potential price variations. Although domestic coal is also getting more expensive due to rising carbon prices, it is still a domestic resource and provides domestic revenues. In the decarbonization pathways, Poland is expected to add more than 20 GW of wind power over the next two decades, making it unlikely to offset the gas replacement with further wind power resources. Given the new geopolitical situation in Europe, large-scale switches to more gas power and any energy system change increasing dependencies on foreign resources can be seen as a potential barrier.

For Norway, the decarbonization pathways show a sharp decline in crude oil and gas extraction and export. Although the Norwegian power system is almost completely greenhouse gas emission-free, the transport sector (large maritime transport sector, and a strong domestic aviation sector) is still heavily dependent on fossil fuels. Further, the revenues from the oil and gas sector as well as its role as a significant national employer are major reasons that pathways showing an end of Norwegian fossil fuel exports before or by 2030 will in reality face strong national opposition from Norway

In the pathways, Estonia is expected to stop producing shale oil already in 2035 and is expected to transition to wind and bioenergy as well as electricity imports. Being a net power exporter, it is credible that extraction can decrease from a security of supply point of view. However, the exports create a significant income for Estonia and hence it is a more challenging change from a macroeconomic perspective. Again, given the latest geopolitical developments in Europe and the transition pathway requiring higher import dependencies and less domestic security of supply can constitute a significant barrier.

4.2 Technology perspective: Natural Gas as Flexibility source

The European climate neutrality target will reduce the usage of power generation from gas while balancing options are needed to cope with a large share of intermittent wind and solar power generation. Therefore, natural gas may be key to guarantee adequacy for short-term operation of the energy system, while its long-term economic viability is rather uncertain. Most of modelling effort have mainly focused on the role of gas in single sectors, thereby lacking cross-sectoral interactions, feedback and consistency. Based on GENESysMod, we analyze the use of gas across multiple sectors and energy carriers: power generation, heat, industry, transport, and buildings. Using GENESysMod, a comprehensive European model, in this sub-section we show that not only a large part of the gas-fired power generation, but also gas transmission and LNG regasification infrastructure in Europe is likely to become stranded by 2050 as a consequence of the Energy Transition.

Natural Gas: Stranded Asset or Cost-effective Flexibility?

Stranded assets are assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities [68]. Some of the main drivers for asset stranding include: disruptive changes in market conditions, societal norms, financial contexts, or regulatory environments [69]. The changes in the regulatory framework to mitigate climate change are a disruptive change. Globally, high shares of fossil fuel based capacities could become stranded in order to fulfill stringent climate goals [70]. Overall, utilizing all fossil power plants that are currently planned, permitted, or under construction either leads to a significant increase in emissions or poses a high risk of substantial economic deficits due to stranded assets [71, 72].

Currently, the power generation assets that under the risk of ending up stranded are coal-fired power plants. In addition, gas-fired power plants face growing uncertainty and risks to become stranded in the next decades. [73]. Arguments to invest in gas-fired power plants are fast ramping and cycling characteristics which is useful for balancing variable renewable generation. Although gas-fired power plants are profitable with low numbers of operating hours, renewable generators with their low variable cost induce very low prices on electricity spot prices and thus further reducing the operating hours of gas-fired power plants [74]. With diminished use and hence reduced profitability, gas-fired power generators might be pushed out of the market and become stranded assets. Furthermore, countries like the Netherlands have already announced plans to replace natural gas in household heating systems [75]. Also the decarbonization of carbon-intense industry have started paying attention to several new low-carbon technology options [76].

Consequently, with reduced demand for natural gas across sectors, the transmission infrastructure for natural gas and liquefied natural gas (LNG) faces the same risk of stranding [77]. Even if natural gas can play a bridging role in the energy transition, total consumption in the EU is bound to decrease [78]. Overall, reaching the long-term goals of the Paris Agreement and the European climate targets implies that fossil fuels have to be phased-out of the energy system (at least to a large extent), potentially relying on 100% renewables in the power sector by 2050 [79, 80, 81]. Another possibility of reaching climate targets would be to rely on the deployment of carbon capture ans storage (CCS) systems. Hereby, conventional generators and fossil fuels can stay in the energy system as their GHG emissions are being captured and stored. However, the technological availability of large-scale deployment of CCS is still uncertain [82, 83]. In stark contrast to this outlook, the numbers of installed gas-fired power plants is rising throughout Europe [84]. In light of stringent decarbonization targets for the European energy system, what is the risk that these might end up stranded?

Maintaining an operable gas transmission network is crucial to guarantee the security of natural gas supply (a central element on the current energy security package of the [85]). Hence, new infrastructure projects diversifying the natural gas supply are planned and under consideration. However, considering strict decarbonization targets, new gas infrastructure may be exposed to a high risk of ending up stranded. Furthermore, decarbonization efforts in the industry and buildings sectors may lead to an overall reduction on gas demand. Combining the development of these sectors and the power system will be central to understand the cost and viability on maintaining the gas infrastructure. This has received limited attention in the literature. Emerging sector-coupling technologies (e.g., Power-To-Gas or direct electrification, [86]) will enable new decarbonization options for the industry, buildings, and transportation sectors. Therefore, the effects of sector-coupling and electrification on future gas demand in light of stringent climate targets has received limited attention in the literature.

Analysis Framework and scope

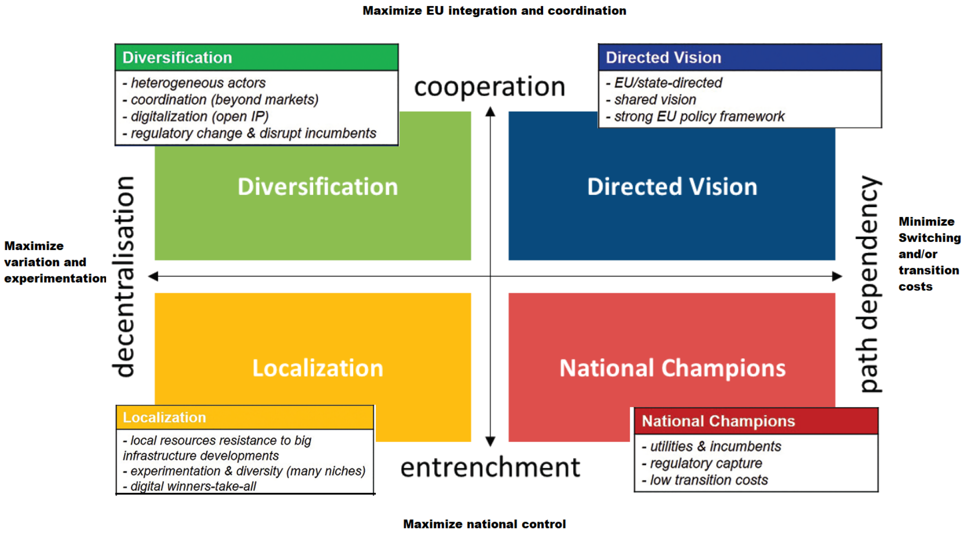

Fig. 12: **The scenarios are shaped by a 2x2 typology driven by the degree of cooperation and level of decentralization. All scenarios have the same decarbonization target but experience different policy environments and technological options.**

In this analysis, we use four pathways for decarbonization of the European energy system until 2050. We address the impacts of these pathways on future natural gas demand in Europe considering sector-coupling and strict decarbonization efforts. As noted, we use the cost-optimizing multi-sector energy system model *Global Energy System Model* (GENeSYS-MOD). The model evaluates the energy system transformation in different regional, temporal, and sectoral aggregation and allows for an analysis with rich technological detail. GENeSYS-MOD chooses investments and operation of technologies within certain boundaries. Commonly, these boundaries include renewable potentials, climate policies (e.g., carbon prices, greenhouse gas budgets, or emissions targets), or exogenous technology development assumptions. GENeSYS-MOD also incorporates the industry, transport, and buildings sectors. The objective of the analysis is to investigate the use of natural gas (technological perspective) in future decarbonized energy system. That is, understand the risk that natural gas infrastructure might ending up stranded.

For the current analysis, natural gas and LNG infrastructure has been included to the model and the data set based on [87]. Liquefaction and regasification plants have been added alongside gas pipelines and LNG imports options. Additionally, new vehicle types using LNG were included. For full details on this study refer to the working paper in [**?**]

The model has been calibrated to the base year 2015. Capacities and production in the sectors electricity, industry, and buildings are fixed for the base year, and can be expanded in future periods. For the transportation sector, the final energy demand and modal shares are given exogenously throughout the model horizon. Other exogenous model inputs include demand and time-series for power, heating, and transportation, hourly availability profiles of variable renewables, yearly energy caps for biomass availability, maximum power capacities for various renewable technologies, yearly carbon constraints, and CCS potentials. The key endogenous variables decided by the model are generation by technology in each time slice, inter-regional trade, investments in new capacity in all sectors, and investment in energy transport capacity. Regarding the natural gas related features and assumption, the model can invest in gas consumption technologies (e.g., gas boilers for space heating, gas engines for industrial steam generation, gas-fired power plants, etc.). The model does not consider a demand for natural gas. Instead, various types of heating demand are included in the model which have to be fulfilled by the available technologies at least cost. Therefore, the consumption projections discussed in the following sub-section (results) are endogenously decided by the model.

Regarding the model implementation, we consider the four scenarios for final demand for electricity, passenger and freight transport, and heat, according to the four pathways defined in the Horizon 2020 Project SET-Nav (Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation, refer to [88]). We use gas demand projections under the four energy transition pathways shaped by two uncertainty dimensions (see Fig. 12): the level of cooperation (i.e. cooperation versus entrenchment) and the level of decentralization (i.e. decentralization versus path dependency). All four pathways are in line with a 2°C target for the European energy system, but with different visions on, technological, geopolitical and socio-cultural trends. In short, we have the *Diversification* pathways which is characterized by heterogeneous actors and a high degree of cooperation and digitalization across Europe. In contrast, *Localization* foresees resistance to the exploitation of local renewable resources and limited support for big infrastructure projects, which leads to a more entrenched scenario. *Directed Vision* is characterized by commonly shared climate ambitions, strong policy framework, and technological and economical cooperation in the EU. Lastly, *National Champions* depicts a future energy system with strong utility companies, regulatory capture, and generally low international cooperation.

Modelling Results

The strict decarbonization targets force fossil fuel usage to substantially decrease until 2050. This affects the most carbon-intense fossil fuels, hard coal, lignite, and oil most, but also natural gas sees a substantial decrease. Dependent on the scenario, annual natural gas consumption declines from its 2015 level of 5000 TWh to between 1000 TWh (-40%) and 3100 TWh (-80%).

GENeSYS-MOD decides to reduce natural gas consumption mainly in the power and buildings sector, whereas gas consumption in the industry sees only a minor decrease. *Directed Vision* and *Diversification* are the scenarios with the least and the largest reduction. In *Directed Vision* some coal and oil-based industry technologies are replaced by natural gas based options (e.g., blast furnaces by direct-reduced iron in the steel industry), which causes higher industrial gas demand compared to *Diversification*. Still, the industry demand for natural gas in 2050 will be lower than current levels. Furthermore, in *Directed Vision* gas-fired power generation plays a more prominent role compared to the other scenarios, even increasing in 2050 compared to 2040. In contrast, *Diversification* sees a substantial decrease in overall natural gas consumption, mainly due to (endogenously assumed) large energy-efficiency gains in the building sector, replacement of gas-fired heating systems, and a strong push for RES in the power sector (as CCS is not available in this scenario). Gas-based heating remains a primary heating source for residential and commercial buildings until 2040, but increasingly more supplemented and later replaced by heat pumps, direct electrification, and biomass. In *Localization* and *Diversification*, from 2040 small amounts of natural gas are used to produce (blue) hydrogen with steam methane reforming technologies. Nevertheless, the main technology for hydrogen production in later periods is electrolysis (green hydrogen).

As noted above, LNG/CNG will not play a significant role in transportation. In contrast, substantial shares of road and rail-based transportation will be electrified, and hydrogen plays a major role in long-haul freight transportation. As a side note, due to lower gas usage for space heating, the seasonal variation in gas consumption will become much lower.

***Table 11:* Aggregate capacity and generation by gas-fired power plants.**

Table 2: Aggregate capacity and generation by gas-fired power plants.

Pathway	Year	*cap*[1]	*gen*[2]	*cf*[3]
Directed Vision	2030	176	565	41%
	2040	134	472	45%
	2050	135	787	74%
Diversification	2030	172	117	9%
	2040	131	105	10%
	2050	59	50	11%
Localization	2030	175	679	49%
	2040	136	630	59%
	2050	109	494	58%
National Champions	2030	176	592	43%
	2040	140	490	45%
	2050	49	94	24%

[1] Total installed capacity in GW.
[2] Total annual power generation in TWh.
[3] Average yearly capacity factor.

In the power sector, only in *Directed Vision*, substantial additions of gas-fired generation are projected. Mainly due to the availability of CCS in the power sector, the total capacity of gas-fired power plants in 2050 stays on 2040 levels in this scenario (Table 11). In scenarios where CCS is not available at all or available in other sectors too, gas usage in power generation is largely reduced. In 2050, the installed capacity of between 59 GW (*Diversification*) and 135 GW (*Directed Vision*) is lower than 2015 levels, indicating that no additional investment in gas-fired power plants is needed to decarbonize Europe. To supplement the large-scale introduction of intermittent RES, some gas-fired power generation remains in the system. In 2050, these plants are utilized for peak generation only in all pathways apart from *Directed Vision*. However, in all pathways other flexibility options, such as power transmission, demand-side management, and large-scale storage (e.g., batteries, pumped-hydro) are preferred to balance variable RES supply. Especially in *Diversification*, natural gas-fired power generation will all but disappear. *Diversification* is characterized by RES-based large-scale electrification.

Here we compare the two most different scenarios *Directed Vision* and *Diversification* for

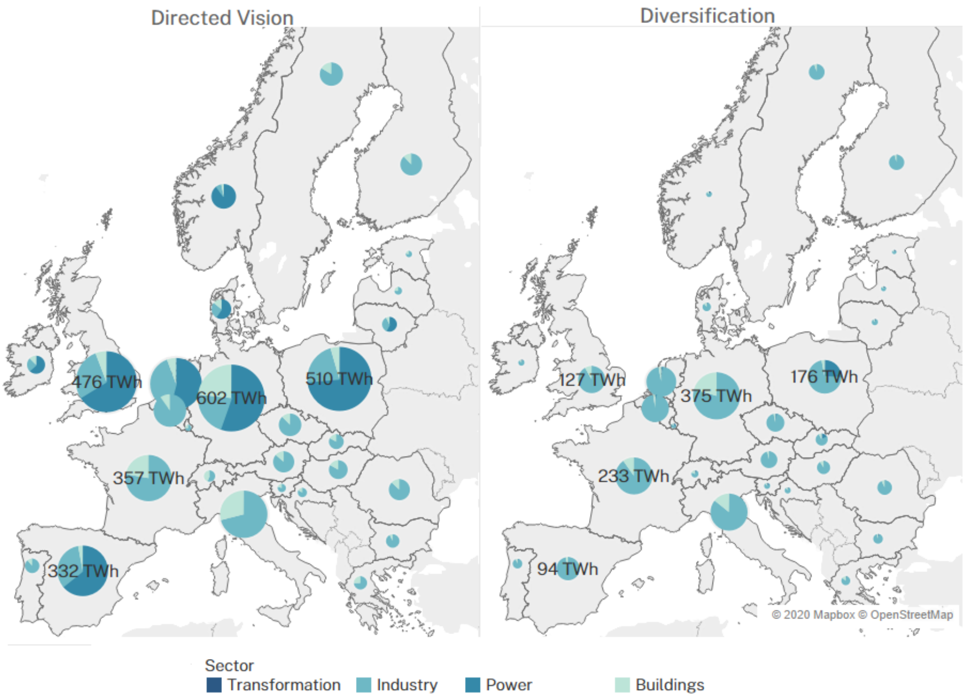

Fig. 13: Natural gas consumption in 2050 per modeled country and sector for *Directed Vision* and *Diversification*. Background map provided by OpenStreetMap.

selected countries. In *Directed Vision* in 2050, Germany, Poland, the United Kingdom, the Netherlands, and Spain still utilize gas-fired power generation. These countries are also the ones with highest natural gas demand in this scenario. In contrast, in *Diversification* power generation is virtually natural gas free; only Poland uses some small amounts by 2050. Country level natural gas consumption reflect this. Gas consumption in the United Kingdom decreases by 73% (from 476 TWh to 127 TWh), Spain -71%, Poland -65%, Netherlands and Germany -37%. In most countries in *Diversification* decreased gas usage for building heating causes much lower gas consumption than in *Directed Vision*. Only in the industry sector, natural gas consumption is rather constant in these two scenarios (as well as in the other two). In a cross-sectoral perspective, a least-cost decarbonization of society does not lead to much lower industrial gas consumption.

Barriers and Policy recommendations

Natural gas fired power generation is an important flexibility source in the European power system with its increasing reliance on intermittent renewable generation. Anticipating much larger shares of intermittent renewable generation, combined with increasingly stringent GHG emission targets, it is not clear how the role of natural gas will develop in the next decades. Results in this analysis indicate that under-utilization of gas-fired power plants is likely to result in financial losses and unprofitably of natural gas in current energy markets. Therefore, if natural gas are deemed necessary for operational security of the energy system, additional mechanisms have to be developed to render natural gas power plants profitable in the long run. Furthermore, the European Green Deal announces even more ambitious climate targets than analyzed in these scenarios. The stricter climate targets imply that the issues discussed in this analysis are even more pronounced, and further strengthen conclusions concerning risks of asset stranding in the natural gas sector. All in all, the main insights of this analysis are as follows:

- Given current decarbonization targets, no significant investments into either gas-fired power plants or gas transmission infrastructure are needed. Europe has enough gas-fired power generation to facilitate a successful energy transition. This is consistent with other, gas specific, studies such as [89].
- Both gas-fired power plants and gas transmission infrastructure will become largely underutilized and are at risk to become stranded assets.
- The role of natural gas as a source of flexibility in the energy system will be limited after 2030-2035, as strict decarbonization targets push natural gas out in the power sector in most of the scenarios.
- Without cost-competitive CCS technologies, natural gas will be replaced by other technologies in the power sector. Flexibility will be provided by large-scale storage facilities and demand-side management. Only if CCS is cost-efficient and deployed, natural gas might have a prolonged role in the power sector.
- A lower gas consumption has a positive impact on energy supply security, as the energy-import dependency for Europe is substantially reduced, and Europe becomes self-sufficient in power and heat generation based on locally produced renewable energy.
- All scenarios foresee a prolonged utilization of natural gas in the industry sector. However, upward pressure on tariffs to maintain revenue requirements on underused infrastructure, or even decommissioning of infrastructure, would decrease the relative competitiveness of natural gas in the industry and other non-electricity sectors.

The analysis indicates that natural gas will be a central transitional technology and flexibility provider as the RES deployment increases in the one and a half decade. To ensure this role, the following policy commentary and suggestions are relevant:

- Spatial flexibility needs to manage large-scale renewable deployment may require investment in gas-fired power plants to relieve region-specific capacity adequacy problems. Where local circumstances merit such specific investments, market designs should allow for region specific incentives, for instance via capacity markets.
- Risk of stranded assets. Consider regulation opening-up co-ownership for gas power plants for different functions where transmission system operators use them to provide ancillary services (or as spinning reserve) and companies to supply wholesale markets.
- System adequacy in a RES-dominated energy system. Market designs should reward cost-effective flexibility beyond the energy sector. Contracts, auctions or tradable certificates for flexibility provisions via interruptible supply. Another example, consider cross-sector policy measures that creates capacity markets that are multi-sector and multi-carrier.

- Although natural gas usage will stay at higher levels longer in industry, eventually the sector will also have to decarbonize, if not offset large amounts of emissions via negative emission technologies. Countries should not hide behind international competitiveness considerations, but remove implicit and explicit subsidies on gas usage for the largest users, thereby incentivizing energy efficiency and decarbonization.

- Consistent policies and research directives on: i) CCS demonstration and incentives for its commercialization and uptake, and ii) technological development in steam reforming and other green gasses, to accelerate learning and drive down costs. Such initiatives will bring provide signals to the gas industry under which conditions gas may stay a cost-effective flexibility provider.

4.3 Consumer perspective

For an envisioned transition pathway to not face drastic headwinds, final consumers are an important actor to take into consideration. Consumers, and, in a wider sense, the general public of the transitioning economies hold power through both their consumption choices and their choices in future elections. Consumer groups can be affected differently depending on the national context they belong to or the consumption type that they are characterized by. The national perspective has already been analyzed above and here we will concentrate on two different types of impacts on final consumers, namely we have assessed the pathways' potential impact on jobs, which directly relates to income and therefore overall consumption capacity for both the fossil-fuel energy sector and the transport sector.

The single most important factor that determines the end consumers ability to consume, and with that their general consumption pattern, is their economic status. Except for the richest people in society, this status is to a large extent determined by their income and therefore their employment. Jobs are hence one of the most determining factors for the level of end-user consumption.

Negative impacts of an unmanaged transition	**Potential positive impacts of a managed transition**
Job losses in fossil fuel industries and businesses around them	New jobs in new industries, skills development Possibility to replace dangerous and unhealthy jobs (e.g., in mines) with new and safer employment
Economic decline of regions	Economic development and diversification, in affected or other regions
Loss of community culture and identity	Potential to "reinvent" regions or communities with new identities
Loss of stable, and strongly unionized jobs	Potential to build up labour representation in new industries

***Fig. 14:* The International Institute for Sustainable Development has assessed the importance of managing the transition to a decarbonized energy system in Europe with respect to the impact on employment and regional economic development. [90]**

Hence the results from GENeSYS-MOD are analyzed with focus on large and fast changes in established industries, which can be translated into major changes in employment availability in a certain sector.

Fossil-fuel energy sectors

All scenarios require a sharp decrease in coal and oil use as fuels for the power and transport sector and a slower phaseout of natural gas. The main oil and gas producing industries in Europe are located in Norway and the UK (for both) and the Netherlands (mainly gas). In the UK the offshore energy production sector is a major employer with up to 30000 jobs directly connected, and an estimated 270000 indirectly related to the current industry ([91]). In Norway, around 200000 people are indirectly and directly employed in the petroleum sector ([92]). Although the absolute numbers are in the same order of magnitude, the percentage these constitute of each country's workforce differs by about a factor ten ([93]) and hence an unmanaged transition would affect total end-user consumption to a different degree. However, most high-skilled employees in the offshore oil and gas industry have been found to have good skill transferability ([94]), making them well-suited for new jobs in the emerging low-carbon offshore industry. Both, the UK and Norway have very good offshore wind potentials, and this sector is expected to grow significantly over the next decades. This holds the potential to offset a considerable part of the expected job losses in the petroleum sector.

The extended coal sector is another important sector highly affected in all decarbonization pathways. Although this sector is not among the most significant employers in Europe, with around 50000 people employed in coal power plants, just below 200000 in coal mines, and another 200000 throughout the coal value chain ([95]), this sector's transformation has to take place in the very near future and hence engages affected consumers strongly already today. Employment in the coal mining sector is highly region-specific and to a large extent centered in very few regions that are otherwise structurally weak. Most affected are four specific regions located in Poland, Bulgaria, the Czech Republic, and Romania, which are each likely to lose more than 10000 jobs in the near future ([95]). Given the demographics and low skill transferability of specifically the coal mining workers, these job losses are much harder to compensate for and can have a significant impact on the consumption levels in the affected regions. Although these regions are not particularly relevant from a European economic perspective, the severity of the effect that the energy transition can have on them is likely to gain national attention and can, if not well managed, result in political developments that can have a barrier effect for an efficient transition. At the same time, if the transition is well managed and the establishment of new industries is successful, this could open up to transform affected regions into more attractive areas with new and safer workplaces. Figure 14 summarizes the findings of challenges and possibilities of managed vs. unmanaged transitions.

Transport sector, automotive and supplier industries

Apart from the fossil energy sectors directly, other sectors of high economic importance for Europe will be affected by the transition. One of the non-energy sectors that need to transform completely is the transport sector. Until very recently, the transport sector, land-, air, and maritime, was almost exclusively powered by fossil energy. Decarbonization pathways that aim for a carbon-neutral Europe by 2050 show drastic changes in the transport sector. This change is two-fold: On the one hand, there is the electrification and change to alternative fuels (H2, synthetic- and biofuels) of the vehicle park and on the other hand, there are structural changes in how passenger transport will function, i.e. more public transport, air to rail, etc.

The European automobile industry alone is estimated to provide about 2,5 million jobs. The transition to electric vehicles, especially passenger cars and trucks, will highly affect this industry. The supplier industry that has grown around the combustion engine vehicle production system will, to a significant extent, lose its existing business model. New industries, especially batteries, will be needed but the skill set and level for those employment opportunities are different, which can result in strong opposition to the transition by workers of the affected industries.

Apart from the structural employment challenges the transport transition will entail, the direct end-user effects are a challenge in themselves. The decarbonization pathways aim for a drastic decrease of combustion engine vehicles for road transport in all European countries already towards 2025 and 2030, with very similar battery electric vehicle introduction curves, see Figure 15. The difference in the situation today and hence the task ahead is vastly different between countries. Two interesting cases are Norway and Poland.

Fig. 15: **Development of road passenger transport in the 1.5 degree openENTRANCE scenarios**

Norway, partly due to its extraordinary economic means, has already built a solid charging infrastructure across the country and at the same time made it economically attractive for its wealthy population to invest in new, battery electric cars, which has resulted in that already in 2020, 50% of new car registrations were electric ([96]).

With historically cheap electricity and higher taxes on gasoline and diesel, electric vehicles became also economically attractive and the transition here can be considered in line with what is needed to adhere to the proposed decarbonization pathways.

Understanding the challenge and potential barriers the transport sector is facing in most parts of Europe, the case of Poland functions as an example: Figure 16 shows the trend in new passenger car registration; a level of only around 2% being electric in 2020.

The car fleet was at around 23 million in 2018 of which there were only around 12000 electric and only about 60% of those were battery-electric. This means that the complete passenger car park needs to be replaced within a decade. Looking at the car market in Poland, a further challenge becomes apparent. Poland has a - in the European context unique - large used car market. A large part of the rural population (around 40% live in rural areas), which is economically weaker than its urban counterpart, is dependent on affordable passenger cars given limited appropriate public transport access. This illustrates the much higher burden on rural, lower-income consumers of the transition.

4.4 Policy suggestions and market-regulatory options to address investments barriers and determinants

The analysis of the three dimensions of the welfare distribution connected to the decarbonization pathways has identified several important potential barriers. On a country level, especially

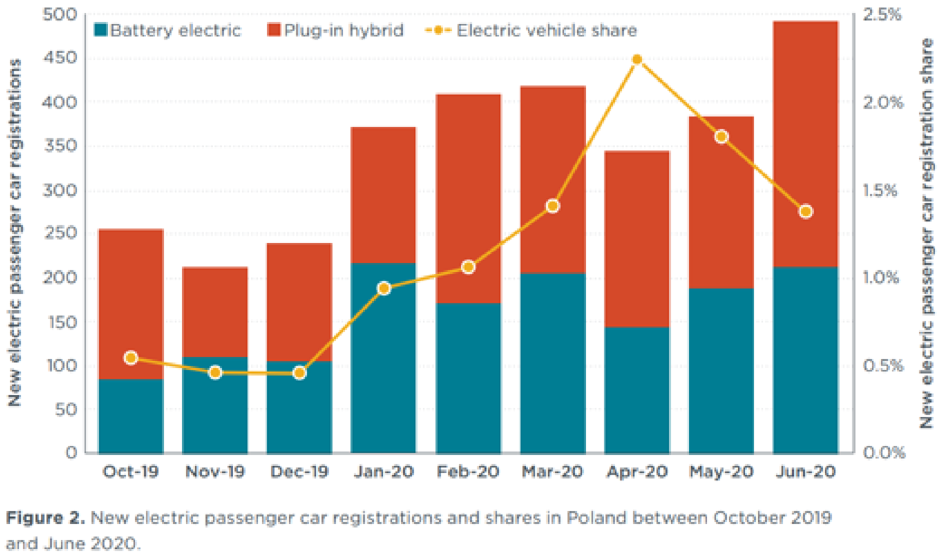

Fig. 16: **New electric passenger car registrations and shares in Poland between October 2019 and June 2020 - [97]**

developments that compromise the risk for higher import dependencies have to be clearly understood and alternatives have to be found. Also, unrealistic developments of the construction and integration of extremely large shares of renewables, especially if the to-be-installed capacities exceed the size of today's power generation system manyfold, can constitute a barrier and should be addressed by adjusting the pathways to ensure a higher likelihood of being policy-relevant. On a consumer level, any developments that will lead to rapid and large changes in the employment options in specific regions or sectors, are prone to become barriers. Here, tailored and well-communicated policies are keys to achieving change that will lead to a beneficial outcome for the affected sector or region. Norway's success story in replacing combustion engine road vehicles with battery-electric ones on a large scale and in a timeframe of just a decade can help inform decision-makers across Europe on functioning policies for achieving this change. However, the differences in consumers' spending abilities and habits have to be addressed sufficiently to lead to the same success elsewhere.

5 Effective policies shaping the future energy system

This section describes the results of the techno-economic analyses on the incentives and barriers to a successful transition towards a decarbonized societal and production system. The focus is initially placed on the economic impacts of the main technical, societal and political assumptions shaping the openENTRANCE storylines, in order to provide a general overview of the possible directions that might be fruitful to take to ensure a balanced trade-off between the decarbonization requirements and the economic growth. Then, the focus will shift to a discussion of the economic effects of potential barriers to decarbonization and its impact on investments. Finally, there will be a techno-economic analysis of cooperative efforts for the decarbonization of the EU production system as well as the analysis of the impacts of potential countries calling off the decarbonization agreements.

5.1 Macroeconomic perspective

The macroeconomic impacts of the four openENTRANCE storylines have been evaluated by singling out the most relevant features of each scenario and mapping those features to several drivers exerting different impacts on the economic system. This evaluation has been carried out under the four openENTRANCE scenarios as well as for a reference scenario, whose GDP, productivity and efficiency levels have been calibrated to match the ones projected by the EU Reference Scenario ([98]) and explained in detail in the openENTRANCE deliverable D7.2. From a geopolitical viewpoint, the quantification of the storylines has focused on the performance of the global economy/markets by establishing a reference GDP and population growth within and outside the European countries. Under the scenarios in which the growth is considered 'uneven', the developing regions outside Europe have been assumed to grow with an expected growth drawn from the OECD scenario ([99]), meanwhile in the case of 'global prosperity', the developing regions outside EU grow slightly faster to catch up with developed regions. Considering the international climate policies, the focus has been placed on the CO2 emission cap development over time, according to the assumptions featured in the openENTRANCE storylines. The development of the markets has been considered placing the main focus on the concept of circular economy. The uptake of a circular economy paradigm has been modeled via a shift from the use of materials to the use of services. Depending on the scenario, different countries might choose to adopt a circular economy paradigm. To implement such a transition, we have reallocated the preferences over the consumption of manufactured goods and services according to the storylines presented for each scenario. For the Gradual Development scenario, most of the countries reduce their preference for materials by 20%, moving this preference towards services. In the Societal Commitment scenario, this amount goes to 35%. Under the Techno-Friendly scenario, this reallocation is only equal to 5%. Considering the climate policies, besides the reduction of the CO2 yearly emission cap, carbon and energy efficiency improvements have been factored in as assumptions. Carbon efficiency represents the reduction in emissions due to decarbonization efforts in industries. In the same way, energy efficiency due to R&D efforts to make industries more energy efficient has been modeled. The level of efficiency is the same for every scenario, including the reference and the Gradual Development scenarios. Both quantification assumptions for energy and carbon efficiency have been taken from the EU reference scenario ([98]). The technology portfolio in energy and transport has been integrated as parameters into the economic modeling. Namely, the technology mix for the consumption of energy commodities in different sectors has been taken from GENeSYS-MOD scenario evaluations for each scenario. More specifically, the shocks considered to model the different storylines in the macroeconomic models are reported in Table 12.

***Table 12:* Implemented shocks in the Macroeconomic analyses**

Abbreviation	Term
Baseline GDP growth	GDP has been calibrated for the Reference scenario to the growth reported in the EU Reference scenario.This has been used as a benchmark to simulate the alternative scenarios.
Population growth	Population Growth has been set to the values considered in the EU Reference scenario.
Materials to services transition	A shift from the use of materials to the use of services has been considered in the preferences of the system.
CO_2 **emissions**	A gradually decreasing cap on CO2 emissions has been included to reduce the consumption of fossil fuels.
Carbon efficiency	A trajectory for the improvement of carbon efficiency has been considered based on the data in the EU Reference Scenario.
Energy efficiency	A trajectory for the improvement of energy efficiency has been considered based on the data in the EU Reference Scenario.
External technology mix	The energy technology considered in the different sectors is defined by a technology-detailer energy system model and used as input dara in the macroeconomic analyses.
Resources extraction	Extraction of fossil resources is gradually reduced towards 2050.

The openENTRANCE storylines have been modeled by considering different mixes of these shocks. The economic analyses show that if the technology changes at a similar pace as the decarbonization requirements, the overall EU economy manages to keep a growth that is only slightly lower than that of a Business as Usual scenario. When considering the GDP it is found that the most impactful measures are (1) improvements in capital and labor productivity (2) energy efficiency, and (3) the cap on carbon emissions. In particular, when comparing the four openENTRANCE scenarios to the reference scenario, it is found that GDP is at most 1.7% lower under the openENTRANCE scenarios compared to the reference scenario in 2050. The lower GDP is due to the much stricter carbon cap in the openENTRANCE scenarios compared to the reference scenario. If we consider the sectoral growth, the evaluation of the openENTRANCE scenarios projects a large increase in activity in the hydrogen sector, (renewable) electricity sector(s), and the service sectors. The activity level of the service sectors increases because, under a circular economy paradigm, the old business model of owning a product is replaced by leasing and/or refurbishing processes. This is particularly marked under the Societal Commitment scenario. Some of the sectors however suffer the consequences of the decarbonization process. Besides sectors related to the extraction of fossil fuels (in particular oil, gas, and coal extraction) some of the energy-intensive industries, such as aluminum production, tend to perform quite poorly partly due to the change in energy input requirements but also due to the shift towards a circular economy paradigm. In general, industry, agriculture, and transport see a reduction of their activity level in all the considered scenarios compared to the reference scenario with a particularly strong emphasis on the Societal Commitment scenario. Among the commodities that experience an increase in demand under the different scenarios, electricity displays quite a remarkable growth, compared to both today's demand and also compared to the demand that would develop under the reference scenario. On average, the demand increases by a factor of 2,5-3 times compared to the demand in 2020. This happens as electricity is the main replacement of fossil fuels in both production sectors and final consumption, besides being used to produce a large share of hydrogen exchanged in the system. On the other hand, demand for fuels decreases for the four openENTRANCE scenarios. The carbon cap forces a shift to energy products that produce lower emissions such as electricity, biofuels, and hydrogen. Demand for fossil-based energy types declines both due to rising CO2 prices and because of technological development, which entails a transition of the energy mix towards a cleaner structure. For what concerns final consumption, i.e. demand from households and governments, the economic models show that demand for fossil-based energy sources decreases when openENTRANCE scenarios are compared to the reference scenario. The analysis of the openENTRANCE scenarios shows that CO2 emissions are decreasing over the years. In the years immediately before 2050, the CO2 emissions are exactly equal to the CO2 cap. This limit triggers a gradual increase in the CO2 price, proportional to the pressure that the CO2 cap exerts on the reduction of emissions. In earlier years after 2020, such price is very small and it is possible that other measures (like energy efficiency or technological change) result in enough reduction in emissions without the need for a push exerted by the CO2 prices. When the carbon budget becomes strict, countries need a steadily increasing CO2 price as a driver to keep emissions within the CO2 emissions cap. The modeling results show that in 2045, the price of CO2 starts to increase exponentially.

The different shocks considered to characterize the scenarios have proved to provide a different impact on the economic indicators. In particular, if we consider the GDP level for the overall EU area, the shocks providing the stronger impacts are both the technology advances and the amount of the allowed annual CO2 emissions. Similarly, a strong positive impact on GDP growth is given by the improvements in energy efficiency. On the other hand, we find that the adoption of a circular economy paradigm, leading to lower consumption of manufactured goods in exchange for more services has almost no impact on the GDP level, but it impacts the contribution that each sector has on the definition of the overall value. In particular, services have a strong increase in value-added which is compensated by the decrease in value-added for both industry and transport. The openENTRANCE storylines are determined according to the changes of three main drivers: society, technology, and policy. One of the main objectives of the economic analyses performed under this project is to simulate how much each of these drivers has an impact on the main macroeconomic indicators. Namely, we focused on determining how much the main shocks related to societal (behavioral) change, technological change, and policy exertion impact the scenarios in which each of these dimensions is predominant. The goal has been to determine, under the relevant scenarios, how much each of these dimensions contributes to growth on one side, and to decarbonization on the other side. When considering the growth side, the main focus has been placed on the GDP difference and on the overall consumption difference between factoring the aforementioned driver into the relative scenario or removing the driver from the same scenario. When considering the decarbonization side, the analysis has been directed at measuring the change in demand for energy commodities in the economy and checking to which extent the considered driver would induce a change in the energy mix.

Societal Driver

The change of societal behavior has been considered in particular under the Societal Commitment scenario where it has been modeled as a gradual shift in consumption from the purchase of manufactured goods to the purchase of services. This would not only mean that future con-

sumption will focus on services per se but that services will also be used to refurbish existing products to ensure them a longer lifespan. In general, the provision of services requires a lower amount of intermediate products. So an increase in demand for services is expected to entail the formation of a smaller multiplier for the economy, as the effects of a purchase of services ripple towards other sectors with lower intensity. This might lead to the definition of a smaller GDP compared to a scenario where circular economy is not adopted, even if the final consumption level grows. On the other hand, the decrease in intermediate expenditure, normally featuring transport and other energy services, results in a large decrease in overall consumption of energy, both clean and fossil. In conclusion, the societal driver, considered as a shift of consumption from goods to services, tends to reduce both GDP and consumption of energy services, whether they are from fossil sources or from renewable ones.
The transition towards a system placing more emphasis on the re-utilization and the refurbishment of products, as well as sharing and, in general, of a decrease in the usage of manufactured goods together with a decrease in demand for goods and an increase in demand of services, leads to a consequent decrease in prices for manufacture and an increase in price for services. On the other hand, the lower use of energy due to the lower production level will lead to a decrease in energy prices, both for clean and fossil fuels as well as for electricity. This contributes to a decrease in transport prices and to a consequent increase in demand, mostly for final consumption.

Technological Driver
The change in technology has been modeled using different types of shocks. The first shock is a change in the energy mix featured in the different sectors based on the information provided by technology-detailed energy system models and the second shock is an improvement in energy efficiency over time on top of the baseline energy efficiency improvement. The inclusion of external developments of the energy mix is considered under every openENTRANCE scenario, while the improvement of the energy efficiency (over the baseline efficiency improvement) has been only considered under the Techno-Friendly scenario. For this reason, in our analysis, we consider the improvement of energy efficiency as the technological driver to evaluate in terms of its potential contribution to decarbonization and economic growth. When considering such a dimension, the technological driver is the only one to display clear positive economic effects, both on economic growth and on final consumption. This quite clearly happens because the lower need for energy lowers the general production costs. The decrease in costs leads to lower prices, which boosts the demand level and induces a large increase in production. This increase in production leads to rebound effects for energy commodities, on the other hand, which offset the initial decrease in demand for fossil fuels, while it leads to a large increase in demand for clean energy. In fact, there is almost no contribution to decarbonization from this factor alone, i.e. the amount of fossil fuels purchased with and without the contribution of the extra energy efficiency remains the same, but it allows decoupling the decarbonization from the growth. This driver is the only one to lead to an increase in GDP and a large increase in final consumption without increasing the demand for fossil fuels. As opposed to the societal driver, the technological driver leads to an increase in demand for both manufactured goods and services. This happens because the assumption used to model improvements in technology are directly related to an increase in energy efficiency, which has the impact of reducing the general price levels and increasing both the intermediate and the final demand. The multiplier effects make this driver the most suitable for ensuring economic growth while switching to a cleaner energy mix.

Policy Driver
Finally, the policy driver has been modeled via the inclusion of a 5% tax rate on the price for the purchase of fossil fuels, coupled with a 5% subsidy rate of the price for the purchase of energy from clean and renewable sources, both starting in year 2025. The combination of these measures leads to an effective push for decarbonization, effectively reducing the amount of utilized fossil fuels and greatly fostering the development of renewable energy production, while at the same time producing almost no effect on the GDP. The effects that the considered policy driver has on the demand for manufactured goods are similar to the ones detected with the societal driver, with a decrease in demand for industrial goods as well as demand for transport and an increase in demand for services, which are less impacted by the general increase in energy prices due to increase in taxation. More about the effects of this driver will be discussed later in the document.

5.2 Stakeholder perspectives and market design alternatives

A successful transition towards a low-carbon socioeconomic system is strongly linked to the ability of developing new clean and affordable energy technologies (e.g., wind power, batteries, solar PV, hydrogen, hydro power, flexibility for energy balance, and others). This development is nevertheless slowed down by a number of factors which make it unprofitable to invest in these solutions. A large part of the studies conducted to shed light on core factors acting as drivers or barriers to investments is based on the use of quantitative modeling tools. These tools can often be more useful in detecting what are the relevant questions to ask rather than providing final answers to this problem. A different view on these factors could be provided by stakeholder opinions, which are necessary to obtain a comprehensive view on the matter and to make the research useful for future projects. To factor the stakeholders' opinion in our study, we have conducted a survey to analyse to what extent some of the economic and regulatory aspects of the investment process in low-carbon technologies might act as determinants or barriers to the uptake of these solutions. In this respect, we were interested in knowing the opinion of actors with different background and areas of expertise about the drivers or barriers to investments in low carbon technologies. The aim of the survey has been to collect the perspectives of stakeholders and the general public to understand what are their views on both economic and regulatory aspects affecting the willingness to invest in new low-carbon solutions. The survey has been forwarded to stakeholders in several European countries and was mostly answered in Norway and Italy, but respondents were also from Portugal, Ireland and Denmark, with the majority being related to academia or research (62%), while the remaining respondents were from the public sector.

The survey was presented with an introductory question asking to evaluate the openENTRANCE drivers in terms of importance from 1 to 3, with 1 representing the highest importance while 3 representing the lowest importance. Figure 17 shows that technological and societal changes are considered as relatively more important compared to policy measures in order to achieve a successful transition (see a more detail discussion on this question in Chapter 2). In particular, possible conflicts for the usage of shared resources such as land and sea have been mentioned as potential barriers which need to be taken into account when defining the path to a low-carbon system and regulation is considered to highlight its role in supporting the development of novel technological solutions.

Under the economic viewpoint, the subsidies to fossil based solutions seem to be less of a problem in European countries compared to emerging countries or USA, since the evaluation

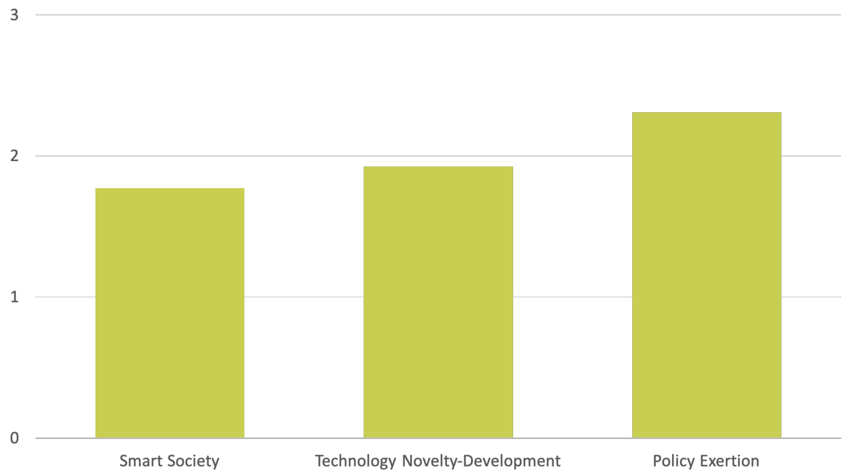

Fig. 17: **Average evaluation of the three openENTRANCE drivers according to the survey. 1=high importance; 3=low importance**

distribution is skewed towards a low importance level, as shown in Figure 18, while more importance is assigned to the time necessary to recover the initial investment and to the development of energy prices (Figures 19 and 20). Finally, the need of a reform in the design of grid tariffs is generally not considered a high priority for the development of low-carbon solutions as shown in Figure 21.

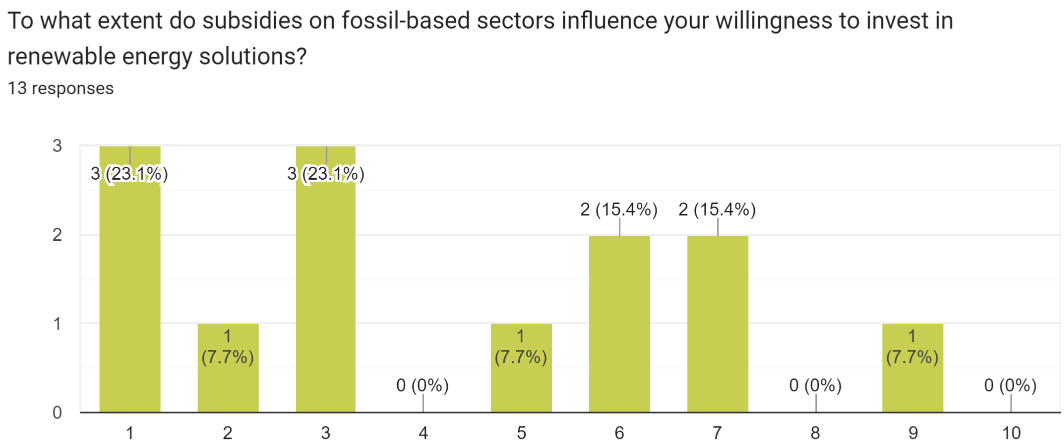

Fig. 18: **Distribution of the importance of subsidies on fossil-based sectors for the investment in low-carbon technologies according to the survey**

The responses have shown to be more uniform in terms of evaluation of importance when it comes to the consideration of the regulatory aspects, with the majority of the respondents agreeing on the fact that a lack of clear rules is highly influencing the willingness to invest in low-carbon solutions (Figure 22). Similarly, the respondents have suggested that the existence of subsidies to support the deployment of low carbon technology are assumed to work as an

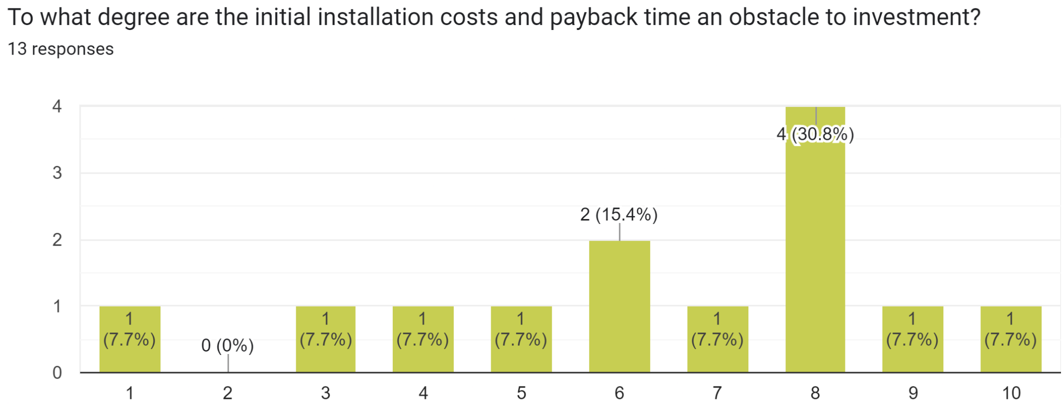

Fig. 19: **Distribution of the importance of installation costs and payback time for the investment in low-carbon technologies according to the survey**

important incentive (Figure 23). Finally, respondents generally assign a medium to high value to the accessibility level to the transmission grid as a determinant to the investment decision, as shown in Figure 24.

Albeit assigning policy a low level of importance among the openENTRANCE drivers, such evaluation seems to be mostly targeting the economic instruments, such as taxes or the adoption of a carbon price, to discourage investments in fossil based solutions. In fact, from the remainder of the survey it becomes clear that the regulatory aspects related to the legislative framework and the definition of rules are at least as important as the economic ones as they largely influence the former. This is in line with the results of the macroeconomic analyses conducted for the openENTRANCE projects and presented later in the text.

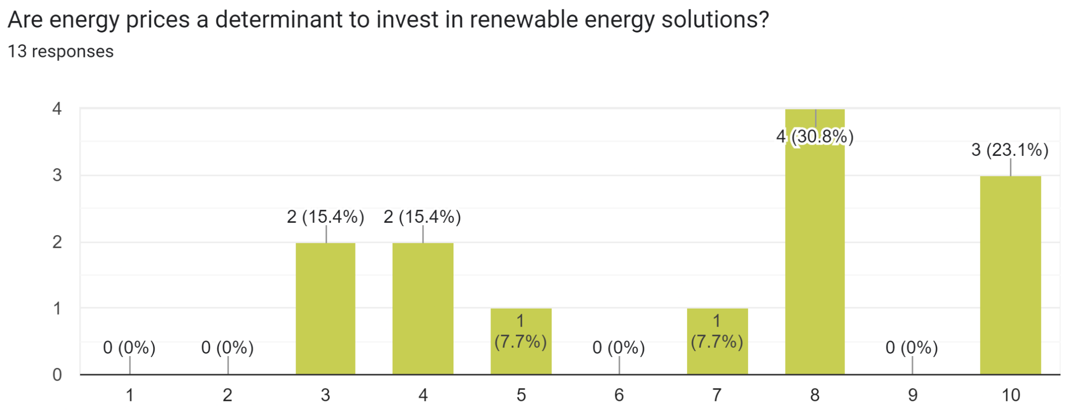

Fig. 20: **Distribution of the importance of the development of energy prices for the investment in low-carbon technologies according to the survey**

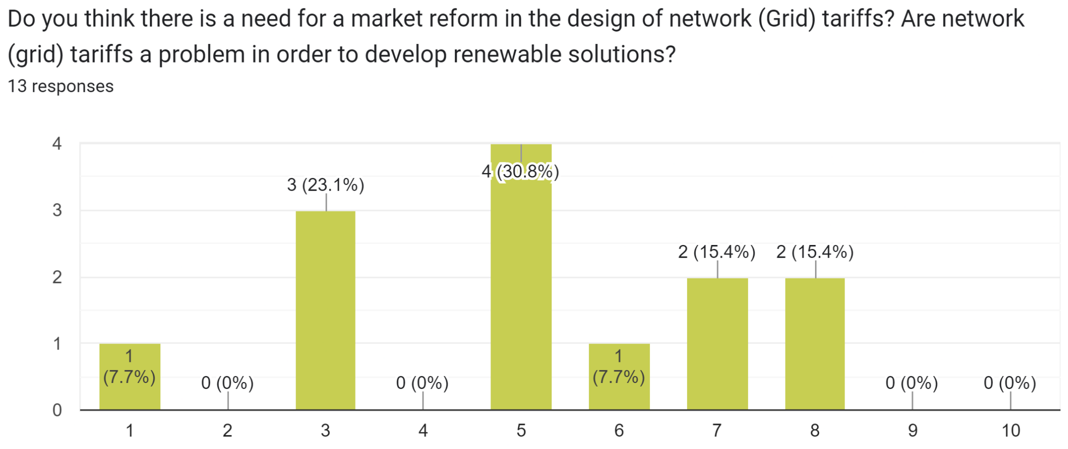

Fig. 21: **Distribution of the importance of a reform in grid tariffs for the investment in low-carbon technologies according to the survey**

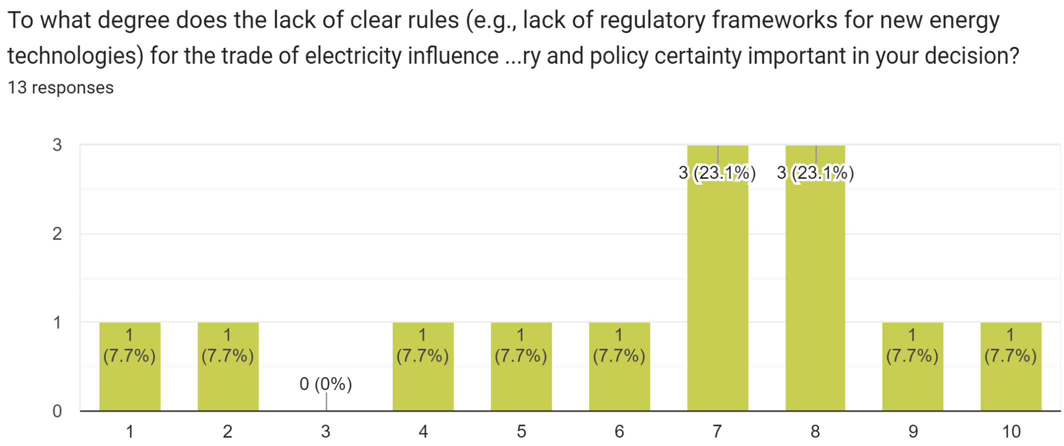

Fig. 22: **Distribution of the importance a clear regulatory framework for the investment in low-carbon technologies according to the survey**

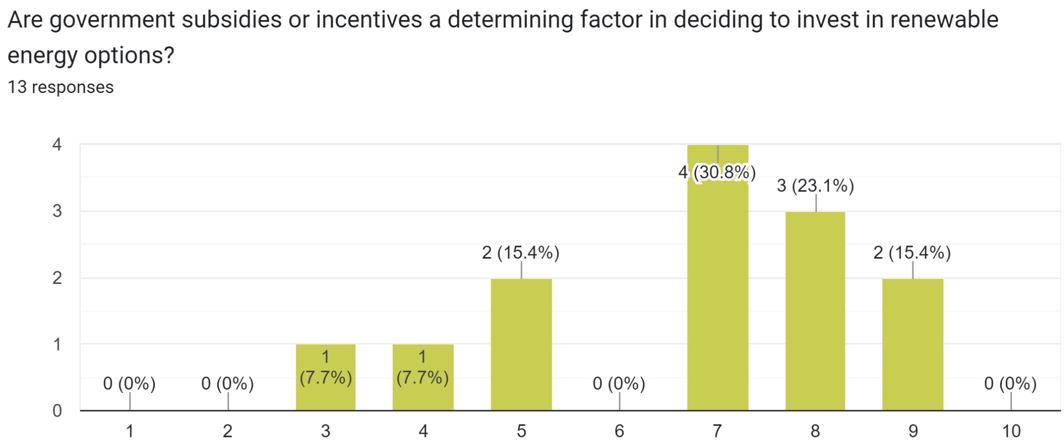

Fig. 23: **Distribution of the importance of subsidies and incentives for the investment in low-carbon technologies according to the survey**

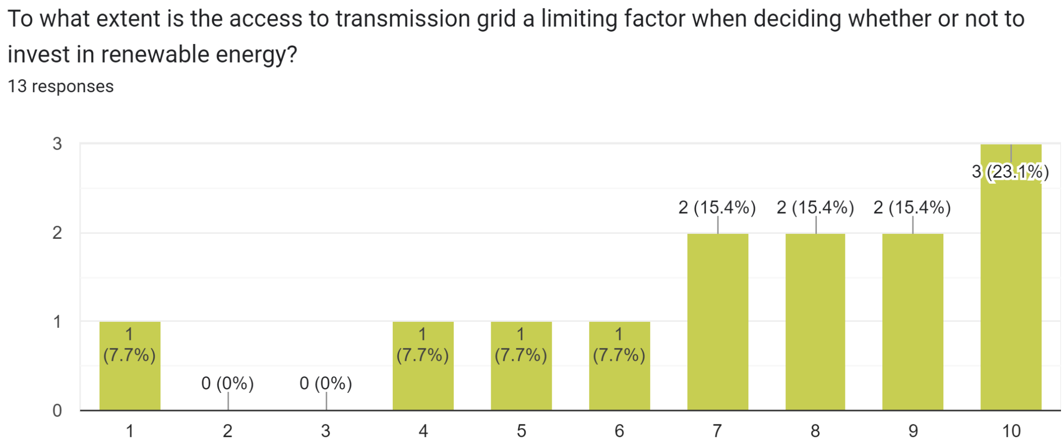

Fig. 24: **Distribution of the importance of access to the transmission grid for the investment in low-carbon technologies according to the survey**

5.3 Policy suggestions and market-regulatory options to address investments barriers and determinants

This section is devoted to the discussion of the effects of some of the main barriers that might prevent the energy system to undergo a successful transition toward a clean structure. Many of these barriers unfairly discriminate against renewable energy by artificially increasing the costs of renewable energy relative to the alternatives. Barriers are often quite situation-specific in any given region or country; we will discuss, three broad categories of barriers: an economic type, a political type, and a technological type.

From an economic viewpoint, many argue that renewable energy costs more than other energy sources, and incentive schemes need to be used to ensure profitability ([100]). The introduction of subsidies can enhance the uptake of renewable energy production and increase investments. We will expand on the discussion made in a previous section and look at the effects on investments of the introduction of a subsidy on the purchase of electricity, financed by a tax on the consumption of fossil fuels. This should both foster the transition of the production of electricity using a clean structure and facilitate the growth of sales of electricity from renewable sources.

From a regulatory viewpoint, there might be restrictions on the use of resources, such as land and sea that could be allocated to the development of a renewable energy production and distribution system. More usually, the lack of a proper regulatory framework, in particular for independent power producers, might curb the private initiative for investments in the development of distributed renewable solutions. Delayed or partially lacking legislation about the rules for electricity trade for small independent producers might make it difficult for them to plan and finance projects due to the lack of consistent rules. Other types of regulatory barriers might come from restrictions on siting and construction. This applies to virtually all production technologies that face building restrictions based on height, aesthetics, noise, or safety, particularly in urban areas ([100]). Other concerns might be related to the safeguarding of animal life and biodiversity or to the competition for land use with agricultural, recreational, and scenic-based arguments. To model the lack of regulation for new power generation we have considered two possible scenarios: (a) considered the effects on investments of a decrease in productivity for electricity generation over time and reduced the speed of transition for the energy mix for power production by setting the same energy mix that is achieved in 2040 under the assumption of the existence of regulation, but for 2050; (b) considered the effects on investments of a decrease in productivity for electricity generation over time and fixed the energy mix for power production to the one used in the base year. This is used to simulate the uncertainty of the rules on which the distributed production might be affected and their repercussion on the lack of transition towards a clean structure. In particular, we have focused on the combined effect that this decrease in productivity and the rigidity in transitioning towards a clean production structure has on the price and demand of electricity and on the impact on sectoral value added as well as on the investments in power generation. Finally, we analyze the consequences of a slowdown of the rate at which technological improvement happens on the demand side by assuming that energy efficiency does not improve over time. This might lead to the purchase of more energy per unit of output, but at the same time reduce the amount of output that the different sectors are producing.

To analyze the effects of economic incentives aimed at reducing the profitability gap between fossil and renewable sources, we have simulated the introduction of a subsidy scheme for the

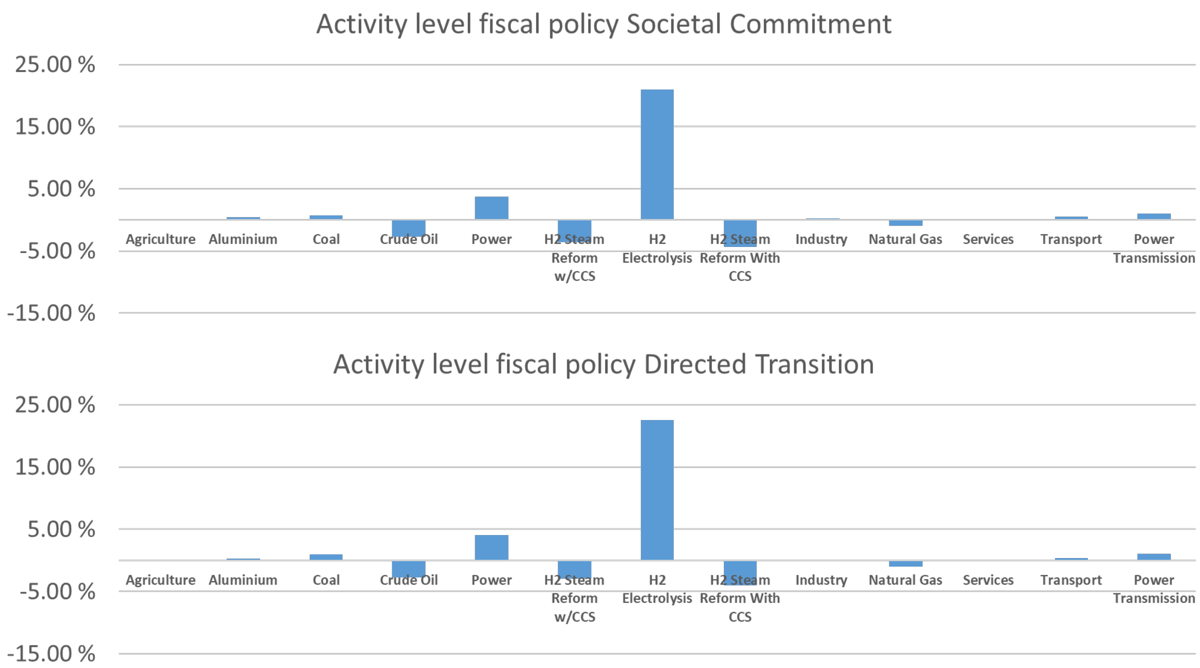

Fig. 25: **Relative change in 2050 sectorial activity level after the introduction of the tax/subsidy scheme compared with the cases without policy.**

consumption of clean energy sources partially backed by taxes on the consumption of fossil fuels. The scheme has been modeled via the inclusion of a 5% tax rate on the price for the purchase of fossil fuels, coupled with a 5% subsidy rate of the price for the purchase of energy from clean and renewable sources, both starting in year 2025. Even if we do not ensure that the revenues collected by levying taxes on the consumption of fossil fuels will be offset by the expenditure to support renewable consumption, these policies can still be used to study the combined effect of taxes and subsidies on fossil energy consumption and clean energy consumption, respectively, as the combination of these measures leads to an effective push for decarbonization, speeding up the process of the development of renewable energy production. The simulation has shown that *ceteris paribus* the impact that such a scheme has on economic growth is rather small, but at the same time is able to foster an increase in the consumption of electricity and speed up the decrease in usage of fossil fuels. This policy has an effect on the energy sector, by fostering an increased growth of power production and hydrogen production using electrolysis, while it further decreases the activity level of sectors linked to fossil fuels, including the production of hydrogen using natural gas. On the other hand, the effect on the largest sectors in the economy such as industry and services is not very prominent as it is shown in Figure 25 where it is possible to notice that the relative change in activity level for services and industry (the largest contributors to GDP) does not change much compared to the same scenarios without the application of the aforementioned policy. Nevertheless, as shown in Figure 26 which displays the percentage change in capital formation compared to 2020, the investments in renewable energy increase slightly faster in the case of the introduction of the considered policy scheme. The results suggest that the use of policy measures such as subsidies for clean energy, supported by taxes can speed up the transition process and incentivize the roll-out of investments in

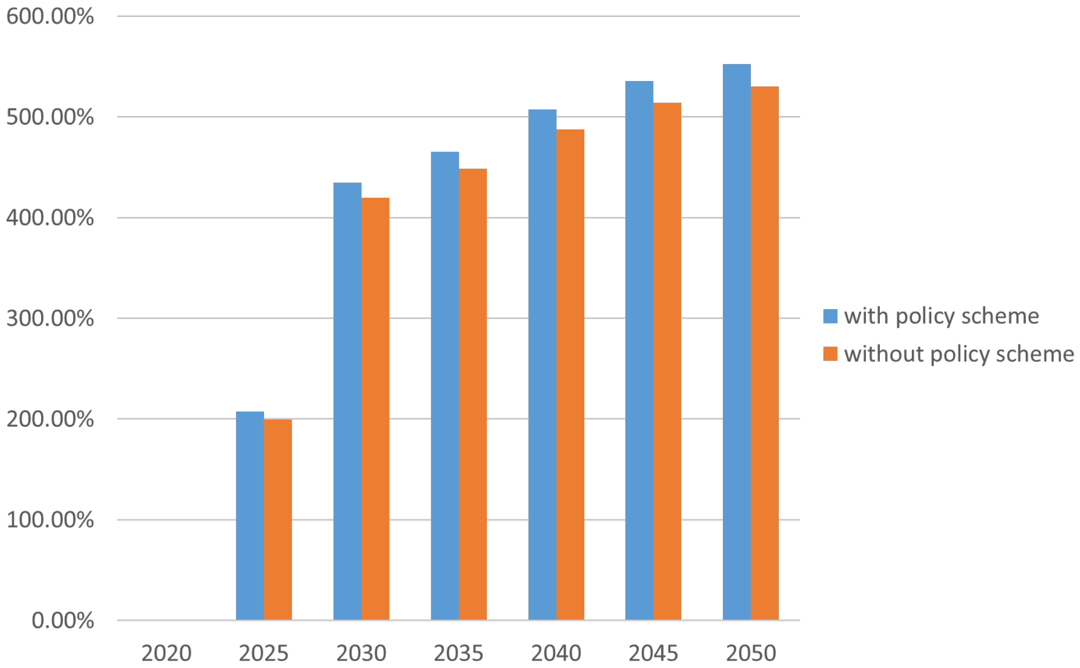

Fig. 26: **Comparison of percentage change in capital formation in the power sector with and without subsidy scheme.**

renewable production without particularly strong effects on the general economy, provided that the production system is transitioning towards a cleaner energy mix. To model the lack of regulatory framework, we have considered the Techno-Friendly openENTRANCE scenario and we have reduced the productivity improvements of the renewable power generation sectors by 2% every five years and reduced the speed at which the power system changes its energy mix considering two possibilities: (a) the transition of the power system energy mix is slower and reaches in 2050 the same energy mix that would reach in 2040 if the regulatory framework was in place; (b) the power system does not transition towards a clean mix and keeps the same energy mix as in 2020. These changes have the objective of curbing the energy transition process on the investment side, while maintaining the push for decarbonization induced by the growth of the price of CO2 allowances. The impact of the lack of regulation on the economic system depends on the degree to which it reduces the speed of technological change in the power sector. Figure 27 shows the effects on the sectorial value added of a lack of regulation implying a slower transition of the power sector and a failed transition case.

In case (a) of slow adaptation of the power sector energy mix, i.e. with a slow transition, we assume that the energy mix in the electricity sector is lagging by 10 years compared to the case with regulation. The impact of a lack of regulation with such conditions leads to higher prices for electricity due to the continued need for usage of fossil fuels in the mix of the power sector, which implies the complementary purchase of CO2 allowances. This makes the older fossil fuels competitive with electricity and still important contributors to the energy mix. The activity level of several sectors related to older fossil fuels is higher in this case than if a regulatory framework had been defined and implemented due to positive spillover effects with the sectors still producing fossil fuels. Moreover, the lower investments in renewables leave more room for

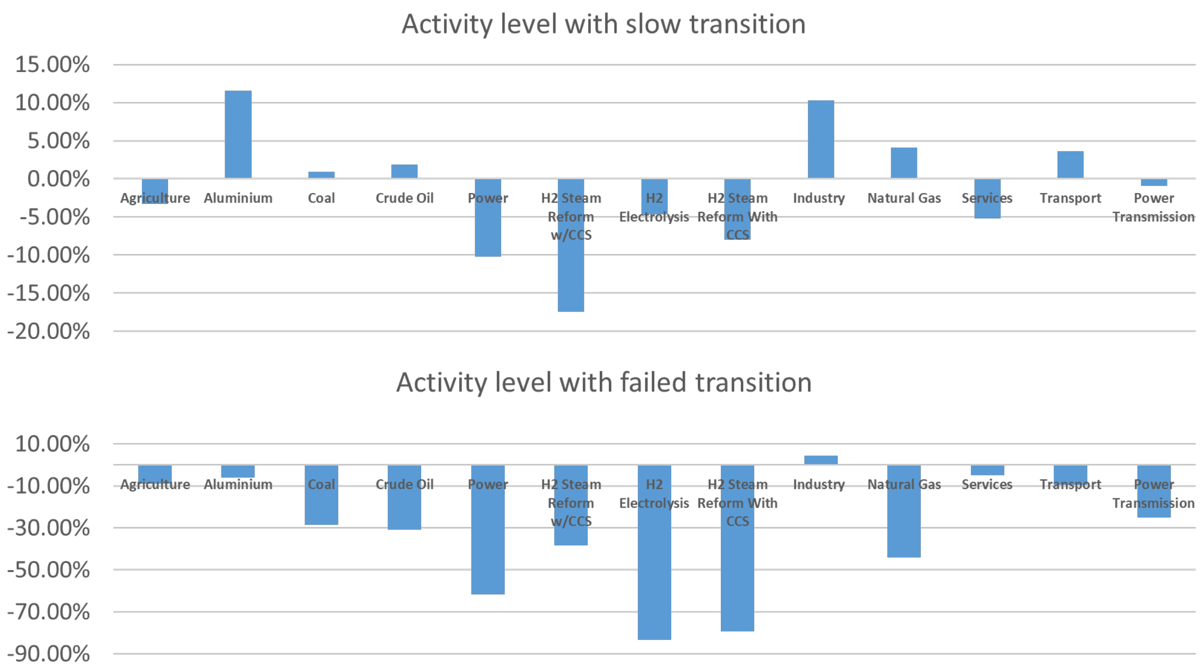

***Fig. 27:* Percentage difference of activity levels in 2050 with slow transition and failed transition due to lack of regulation compared with the Techno-Friendly scenario.**

the employment of capital in industry that can produce its output at a lower price thanks to the larger availability of resources that otherwise would be employed more intensively in the energy transition effort. Therefore, the effects of lack of regulation in case they only delay the transition might allow industry to have larger access to capital and produce more than in the case in which capital is employed massively in the deployment of renewable power production. In case (b) of failed transition, with the energy mix for power production stuck at 2020 levels, the picture is quite different. The CO2 price makes purchasing energy generally very expensive due to the high need for fossil fuels, due to the fact that the policy effort is directed towards banning their presence from the mix. This leads to a generalized decrease in value added for the economy. The lack of transition, paired with the growing CO2 prices leads to a high increase in the price of electricity, whose distribution is portrayed in Figure 28. This leads to problems in actually switching towards a cleaner source of energy for the production sectors due to the general increase in the costs of energy. These increases in costs are due to the increase in CO2 prices for fossil fuels and to the lack of adequate supply for electricity production. This increase in energy prices has an impact on the costs of production and leads to a generalized increase in prices, with repercussions on the growth of the economy. In fact, this version of a regulatory barrier inducing a very slow transition brings one of the strongest impacts on the GDP of the EU countries, with a drop of almost 10% compared to the same scenario with a clear regulatory framework governing the development of renewables. As a consequence of the strong reduction in power demand, the difference in investment growth over the years for the case with regulation and the case without regulation is remarkable. Figure 29 shows the level of capital formation in the power sector as a consequence of lack in the regulatory framework, both under a slow

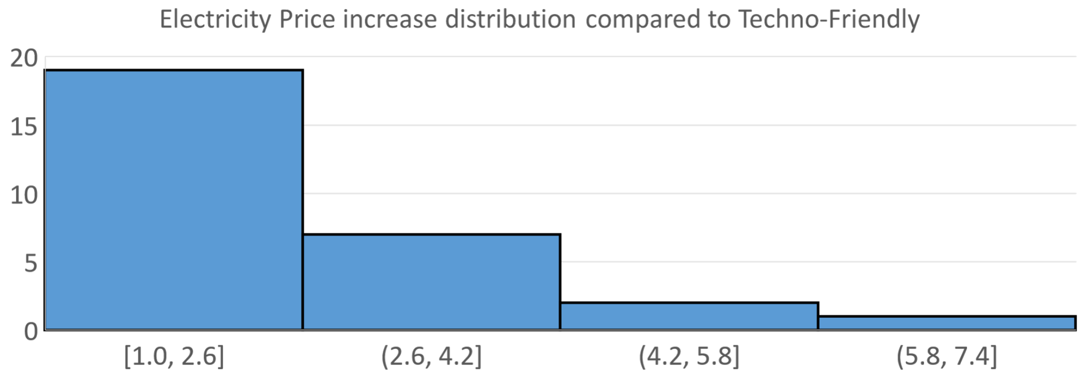

***Fig. 28:* Distribution of electricity prices increase in EU countries when lack in regulation heavily influences the growth of new investments in renewables in 2050 compared to the case with regulation in 2050. The figure suggests that the price might almost triplicate in most countries, but in some of the countries it might reach peaks more than 7 times higher compared with the plain Techno-Friendly scenario without restrictions.**

transition, with the energy mix of the power sector lagging by 10 years compared with the case with regulation, and under the case of a total lack of transition, with the energy mix of the power sector remaining the same as in 2020. While the results obtained in this exercise might overemphasize the effects of a lack of regulation and the level of rigidity in the transition might be more forgiving, they still make a point on the fact that a suitable regulatory framework is paramount to foster the transition towards a clean energy production structure. The general decrease in economic activity leads to a decrease in the purchase of all energy carriers, including biofuels and hydrogen, compared to the case with a clear regulatory framework.

Still, from a regulatory viewpoint, there might be restrictions on the areas where renewable generation can be installed. This barrier to investments has been modeled by partially modifying the structure of the power sector in the macroeconomic model, requiring that the growth of land available for installation is constraining the potential production of electricity. This is equivalent to defining a specific type of capital, held by the households, which is invested directly in the power sector and whose availability is proportional to the availability of new sites suitable for installing renewable production facilities. Moreover, to simulate the fact that the lack of new investments mainly impacts the growth of renewable generation, we have assumed a lag of 10 years in the change of the energy mix for the power sector. Namely, to model the case of site restrictions we have used in correspondence of 2050 the same energy mix that is considered in 2040 in case of no restrictions. We implemented this case study using the Techno-Friendly scenario as the baseline assumption for the rest of the technical and socioeconomic system. The first effect of the lack of licensing for the usage of sites for the construction of renewable power generation facilities is a decrease in the availability of supply of electricity compared to the case without restrictions, as shown in Figure 30, which leads to a consequent general increase in the price of electricity, as shown in Figure 31. The change in price and the availability of electricity supply has a strong negative impact on the production of hydrogen based on electrolysis, which is one of the sectors experiencing the largest loss in value-added, while steam reformation with carbon capture and storage becomes a more attractive alternative for supplying a clean energy

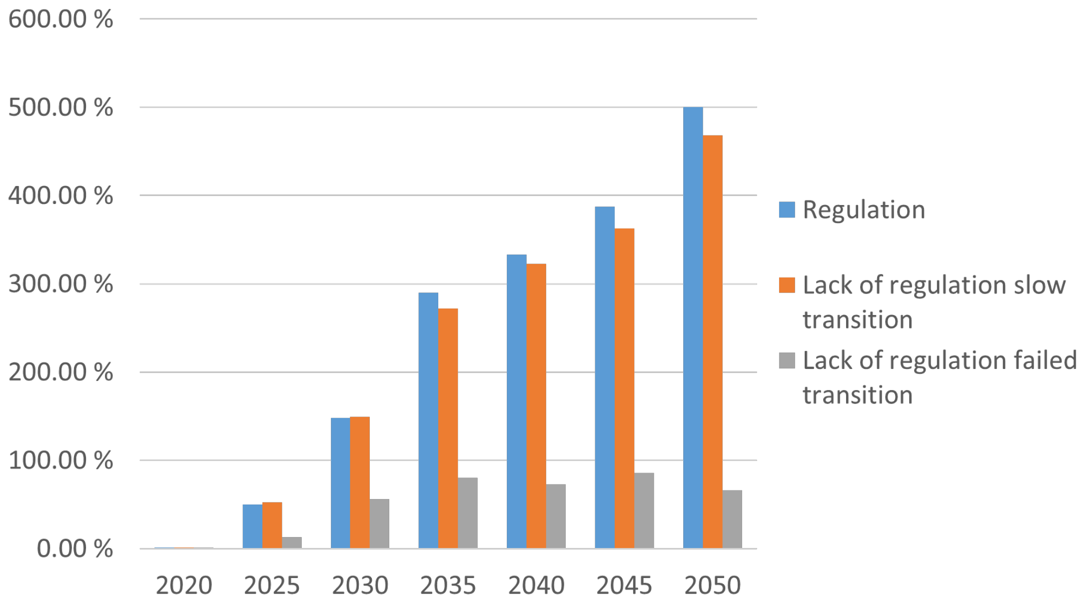

Fig. 29: **Comparison of percentage change in capital formation in the Power sector with regulation and with lack of regulation.**

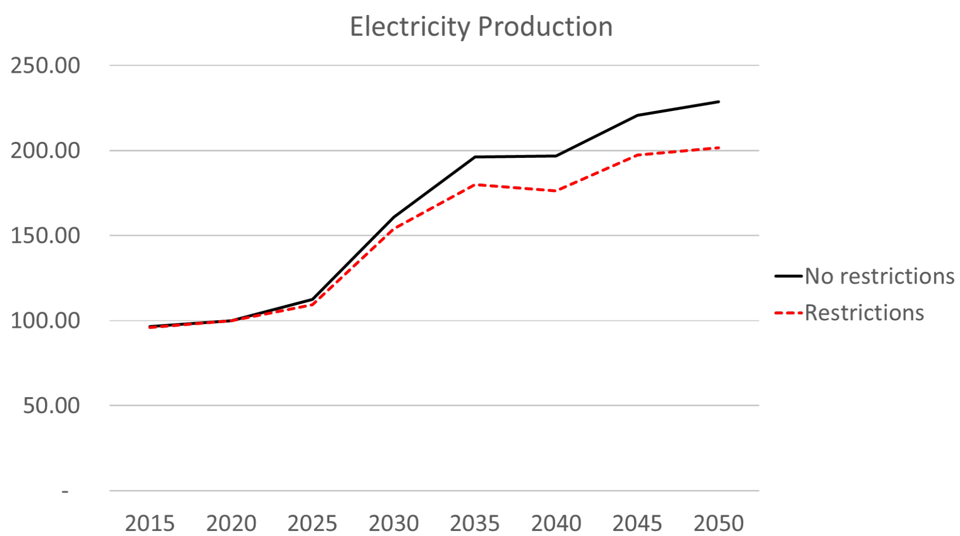

Fig. 30: **Development of electricity demand under the Techno-Friendly scenario with and without restrictions on installation sites. The index for production level in 2020 is set at 100.**

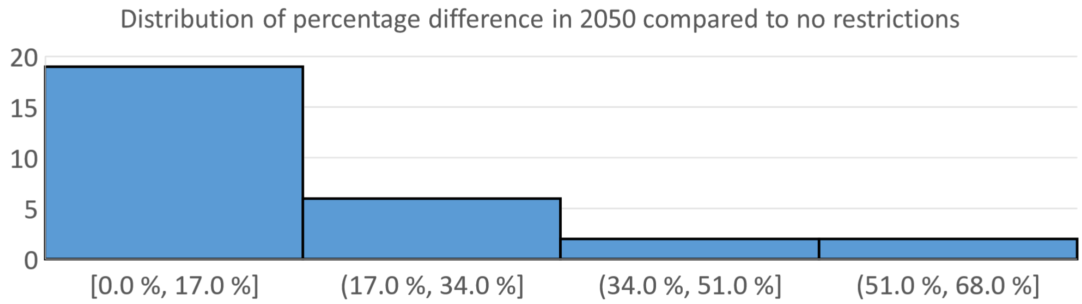

Fig. 31: **Distribution of electricity prices increase in EU countries when siting restrictions influence the growth of new investments in renewables in 2050 compared to the case without siting restrictions in 2050. The figure suggests that the price increase by almost 20% in most countries, but reach peaks of almost 70% increase compared with the case without restrictions in some of the countries.**

source. Both industry and services suffer losses compared with the case without restrictions on the development of power generation facilities, but the results suggest that in the long run, both sectors manage to increase their investments to secure a more efficient production by intensifying the contribution of capital similar to what happens in the case of lack in regulation. These investments in larger capital allow both industry and services to continue producing at only slightly increased prices. The sectors with the largest losses in value added are the power sector, aluminum production and transport, but all manage to stay around 1% compared to the case without restrictions. Similarly to what has been observed in the previous case, the impact on the overall GDP is not as high as one could expect, due to the capability of the larger sectors to attract more capital and produce using lower energy amounts.

We have analyzed the economic and investment-related impacts of three major types of barriers, highlighting how important is to ensure steady technological support for the transition. Technology availability and its support by regulatory institutions have proved to be the main driver to a successful transition of the economic and energy system towards a low-emission structure. Other barriers such as failed institutional collaboration between European countries will be analyzed in the next chapter.

6 A Top-Down/Bottom-Up modeling framework to cover short-term and long-term impacts as well as reciprocal effects of the energy-economic system

Climate change is at the center of the international debate as its impact is expected to disrupt the stability of the economic and social system. Already today some of the effects of this process start to be perceived with the emergence of extreme climatic events. The impacts that global warming might have are not only environmental but will ripple through the economic and societal structure. This calls for the development of policies that need to pave the way for the decarbonization of the production system in order to contrast the processes leading to climate change. The European energy transition envisions at least 60-70% incidence of RES as part of the final energy generation share by 2050. This transformation of the energy system will be carried out on a systemic scale and will therefore not only affect all major energy carriers but also have implications for the European economy. The decarbonization of the energy system will have an impact on the costs and the productivity of the industry and the outcomes of this transition may be counterproductive from the economic viewpoint if not carefully planned. For this reason, a thorough analysis of the possible future transition scenarios should not only limit itself to the technical feasibility but also consider the overall impact on the economic system. The concurrent analysis of the technical and economic outcomes of possible storylines about the development of the technical, societal, and political dimensions can be carried out by linking models each covering different aspects of the energy transition.

Among the levers available to the policy maker to foster the transition there is the use of CO2 allowances, which must be purchased alongside any fossil fuel in proportion to the amount of emissions that such fuel produces when used in a particular sector. The price of these allowances increases with time as a consequence of the gradual decrease of the cap on CO2 emissions, which makes these allowances more scarce. We analyze the impact of carbon price policies on the European energy system and economy and try to assess, in absence of other instruments, how much this energy transition constitutes an economic turn-down. Furthermore, we analyze to what extent a tariff on imports from potential countries calling off the agreements on energy transition could work to ensure cooperation on a climate policy level. We carry out the analysis by linking REMES-EU, a multi-region dynamic Computable General Equilibrium (CGE) model with GENeSYS-MOD, a least-cost based technically detailed model of the European energy system. The main questions that we aim at tackling are related to the ability of RES to offset the lack of fossil fuels by 2050, how much technology will play a role in fostering the transition while ensuring continued economic growth and what is a projection of the economic effects of the decarbonization in different EU countries. The remainder is structured as follows: Subsection 6.1 describes the models involved in the common analysis framework as well as the linking methodology adopted. Subsection 6.2 outlines the scenarios developed for the case study, while Subsection 6.3 discusses the results of the common analyses.

6.1 Models and linking method

GENeSYS-MOD is a cost-optimizing linear program, focusing on long-term pathways for the different sectors of the energy system, specifically targeting emission reduction targets, integration of RES and sector-coupling. The model minimizes the objective function which comprises total system costs (encompassing all costs occurring over the modeled time period)

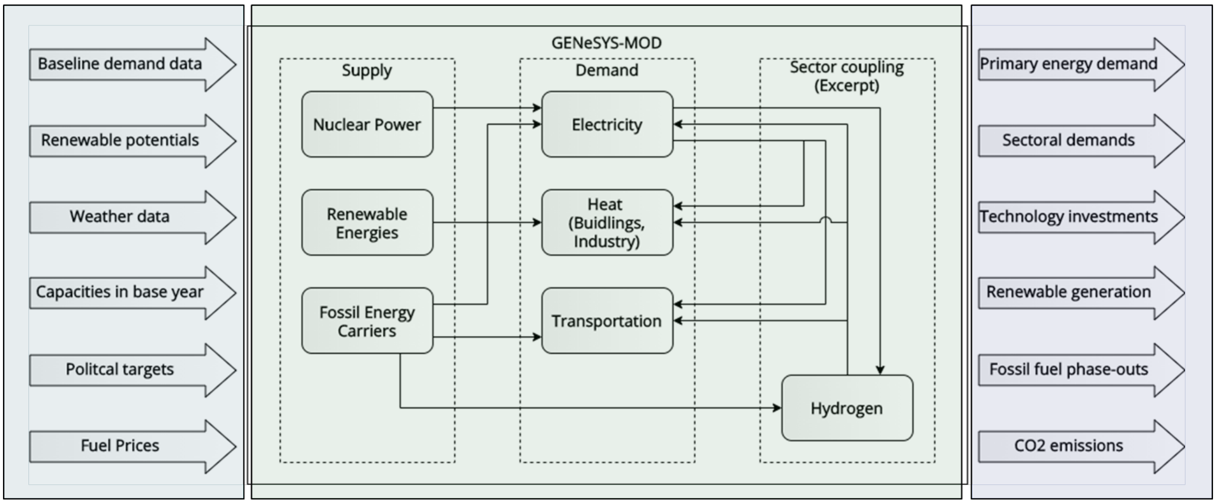

Fig. 32: **GENeSYS-MOD structure**

and was used in multiple case studies analyzing regional, continental or global energy system ([101, 102, 103, 104, 105, 24]).[4]

Energy and energy service demands for the electricity, buildings, industry, and transportation sectors are given exogenously for each time step, with the model computing the optimal flows of energy and the resulting needs for capacity additions and storage. To achieve these results, the model can choose from a plethora of technologies spanning across the mentioned sectors, with sector-coupling and storage options being key functionalities. Constraints, such as energy balances (ensuring all demand is met), maximum capacity additions (e.g., to limit the usable potential of RES), RES feed-in (e.g., to ensure grid stability) or emission budgets (implemented either yearly or as a total budget over the modeled horizon) are given to ensure proper functionality of the model and realistic results. Figure 32 portrays a stylized version of the general structure of the GENeSYS-MOD model. On the far left, we have the input data used in the model while on the far right we have the main output that the model is providing. The model itself is composed of three blocks; (a) a supply block that considers the production technologies for different energy carriers. These technologies provide electricity to the grid and extract resources from raw energy carriers that also provide energy for industrial and residential heating, (b) a demand block considering the total demand for energy services, (c) a module for sector coupling for Power2X capabilities. The model uses a range of technology options to fulfill the demands for electricity, heat, and transportation, while keeping the constraints, such as renewable targets or emission reduction goals, satisfied. To achieve this, the model optimizes the construction of new capacities of generation facilities, sector-coupling options, and energy storage. This allows the definition of the cost-optimal pathway compatible with the long-term scenarios for all sectors.

REMES-EU is a top-down CGE model with focus on the energy system. It is modeled as a mixed complementarity problem, a mathematical structure that allows to define complementary conditions linking mathematical expressions in form of inequalities to non-negative decision variables to ensure that either the inequality is satisfied strictly or the connected variable is

[4] For more information about GENeSYS-MOD including documentation, quick-start guide, and sample dataset, the reader is referred to: https://git.tu-berlin.de/genesysmod/genesys-mod-public

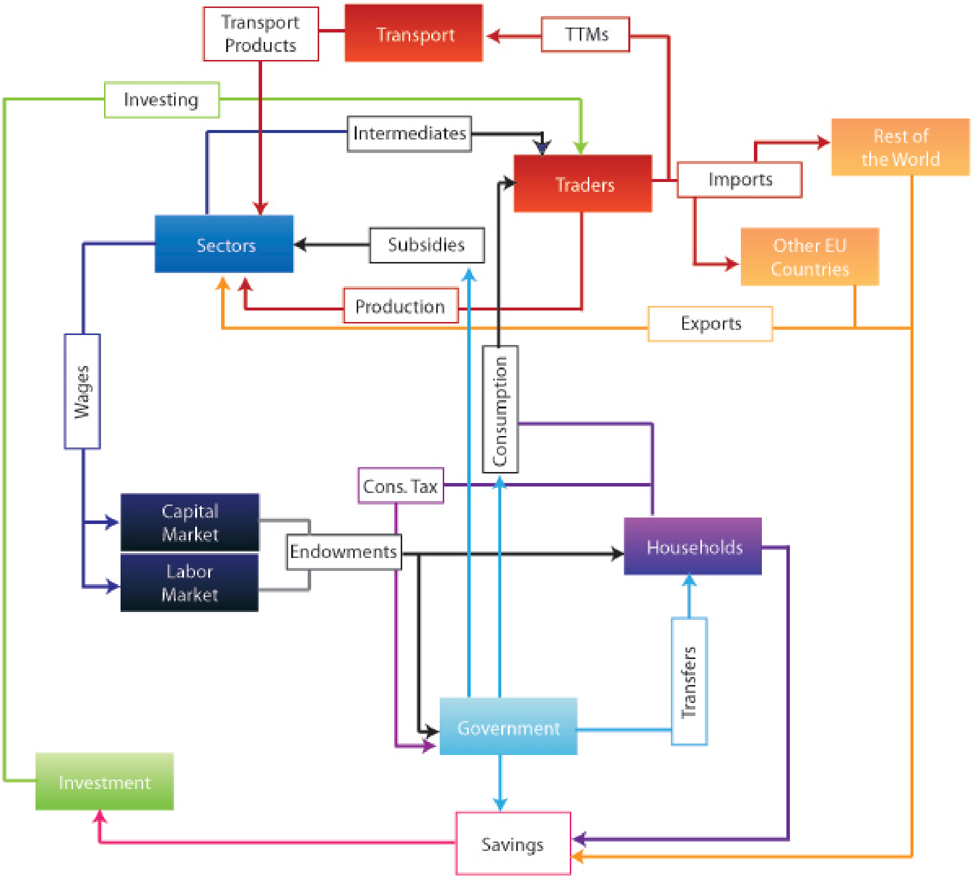

Fig. 33: **REMES-EU Structure**

zero. The model covers the economies of 29 European countries, composed of the EU26 group except for Croatia, but with the addition of Switzerland, Norway, and the UK. In each country, consumers are demanding goods in order to maximize utility, and producers are supplying goods in order to maximize profits. Each country is described by its social accounting matrix (SAM), which defines the money flows in a particular year. REMES-EU models the behavior of both production sectors and final consumers as they tend to establish an equilibrium between demand and supply of each commodity in the economy as a consequence of a given change in the economic system conditions. These changes can be the definition of taxes or subsidies, the variation in the availability of one or more resources, changes in production technology or consumption preferences, as well as sectoral productivity levels. Resources explicitly modeled in REMES-EU include natural resources availability, labor force availability, and carbon allowances availability. The model can be used for analyzing the impact of European policies on the economy of the different countries in terms of GDP, prices, sectoral value added, unemployment, sectoral and commodity monetary input/output, and CO2 emissions. REMES-EU considers monetary flows among EU countries and works on the basis of fully balanced national SAMs with detailed international trade flows and transport margins. The model implementation allows for a flexible nesting structure. The nesting structure and substitution elasticities used in this study are presented in [106]. The work has been inspired by several spatial CGE models such as PINGO ([107]), RAEM ([108]) and RHOMOLO ([109]). Each agent in REMES-EU is represented on the

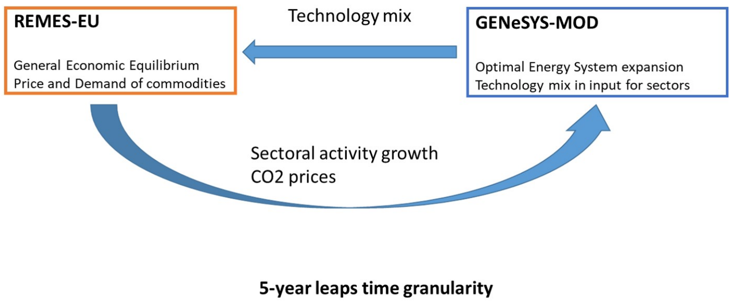

Fig. 34: **Linking procedure between REMES-EU and GENeSYS-MOD**

national level and comprises a representative household, a representative producer in each sector, a trader for each good acting according to the Armington assumption, a local government, and a local investment sector. We define production functions using a KLEM structure in REMES. We use elasticities as reported in Koesler and Schymura ([110]), but we assume a Leontief nesting of the energy goods in order to exchange data with bottom-up technology-rich energy system models. The monetary flows featured in REMES-EU are represented in Figure 33. In the diagram, traders buy from internal production, imports and transport, and trade margins and sell to everyone else (consumers, government, investors, and industries). Households buy from traders, send savings to investments according to a pre-specified propensity for savings and pay taxes. On the other hand, they receive money from transfers and endowments from the capital and labor market. The government buys goods and services from traders and sends transfers to households, receiving money flows from taxes. Investors buy from traders and receive savings from government and consumers. Industry buys materials and energy commodities from traders and repays labor, capital and taxes while receiving money from traders and governmental subsidies. Finally, the rest of the world buys from industries (exports) and sells to traders (imports). The production of goods is represented through a three-nest constant-elasticity-of-substitution (CES) function, assuming a typical KLEM structure.

The two models are soft-linked by a bidirectional exchange of results. Namely, GENeSYS-MOD provides a technology-rich based dynamics of the technology changes in terms of energy inputs structure required by the different sectors and final consumption. For each sector, GENeSYS-MOD provides the demand for energy commodities in EJ per year. This is considered an input in REMES-EU. As a response, REMES-EU provides the percentage change in sectoral activity level with respect to the base year as well as an updated projection of the CO2 price in EUR/ton. The procedure utilized to soft-link the two models is shown in Figure 34. The two models use different unit measures to quantify their variables; REMES-EU uses monetary-based input data, consisting of the flows of money from each source and destination among the participants in the economic exchanges, while GENeSYS-MOD is based on physical quantities, with the different energy carriers considered in Exajoule. The external technology shares provided by GENeSYS-MOD to REMES-EU have been included in the following manner:

- If both models include the commodity, then the change is multiplicative, i.e. the change in share is obtained by multiplying the percentage change in the considered year compared to the base year from GENeSYS-MOD and applying it to the initial data in REMES-EU to reconstruct the counterfactual share in the production function over time according to GENeSYS-MOD.

- If REMES-EU does not have the commodity at the beginning, then the change is additive, i.e. the difference in share is considered by subtracting the value that GENeSYS-MOD displays in the considered year to the value considered in the base year.
- If GENeSYS-MOD does not have the (polluting) commodity at the beginning, then it is phased out under decarbonization-based scenarios in REMES-EU.

6.2 Scenario definition

The scenarios used in this exercise differ from the openENTRANCE ones as these do not contain the same extensive amount of information related to the societal, technical, and political aspects of the transition, but only capture some essential features, such as the decarbonization need via the definition of a carbon cap and the differentiation of the decarbonization efforts among the countries. We consider four possible scenarios, defined according to the status of two key drivers: a) the level of decarbonization, linked to the change in availability of CO2 allowances, and b) the level of cooperation towards a collective decarbonization effort. More precisely, we characterize the decarbonization level by assuming both technical improvements and policy measures. On the technical side, we assume that the productivity related to the production of electricity from renewables increases over time under the decarbonization scenario, while on the policy side we assume the adoption of carbon allowances that need to be purchased alongside energy commodities from fossil sources and whose availability decreases over time, inducing an increase of the CO2 price. The relative reduction in the availability of the allowances depends on the emphasis placed on the decarbonization target and will therefore change depending on the considered scenario. We define the level of cooperation on the basis of the consensus on the adoption of the system of allowances by all European countries. Namely, if cooperation is not contemplated, some countries might decide to unilaterally call off the decarbonization agreements and stop using the CO2 allowances mechanism to facilitate the energy transition. In case of a lack of cooperation, the countries still engaging in the collaborative effort of decarbonizing their production system might respond by setting tariffs on imports from the countries calling off the agreement. The four scenarios stemming from the adoption of the decarbonization/cooperation drivers are displayed in Figure 35.

The models have been jointly used to evaluate the technical and economic repercussions of two possible scenarios under mutual collaboration assumption: a Business as Usual scenario and a decarbonization scenario of the European countries, while the case of decarbonization with lack of cooperation has been only analyzed using the macroeconomic CGE model.

To include the scenario features and create shocks for the REMES-EU, model we have defined a CO2 allowances system for each country. Namely, each sector must purchase CO2 allowances alongside fossil fuels in proportion to the emissions that such sector produces when consuming such fuels. The price of the CO2 allowances is related to their availability within the economy, and their availability is gradually reduced towards 2050 to match the decarbonization goals. The evolution of the energy requirements of each sector are considered external data and included from the results provided by GENeSYS-MOD. We consider the improvement of energy efficiency over time for each sector and country and assume an increase in the productivity of renewable production by 1% per year. The macroeconomic model has been calibrated to match the GDP growth of the EU reference scenario in the BAU scenario in correspondence with the first iteration of the linking procedure. The intensity of the considered shocks is different under the two scenarios. Table 13 presents a summary of the shocks used for the economic model

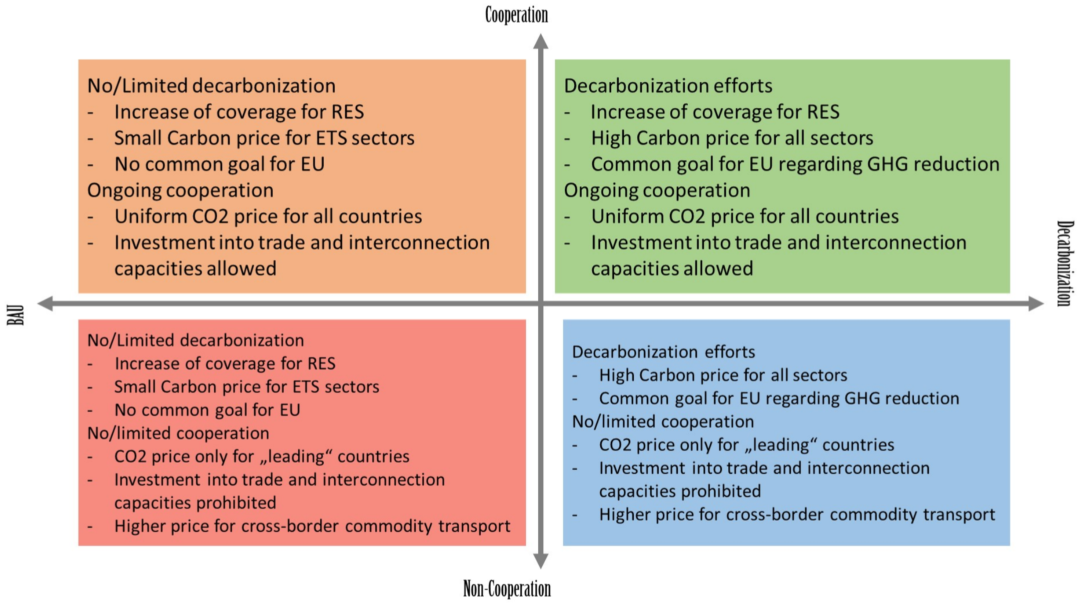

***Fig. 35:* The four scenarios of the case study**

under the BAU and the decarbonization scenario.

***Table 13:* Translation of scenario features into quantitative input to the macro-economic model**

Shock	Bussines as Usual	Decarbonization
CO2 emissions	CO2 cap decreasing by 60% of the 1990 emissions level.	CO2 cap decreasing by 90% of the 1990 emissions level.
Energy efficiency	Improvement based on data from EU Reference scenario. The improvement ranges between 1% and 2% per year depending on the country.	Improvement based on data from EU Reference scenario. The improvement ranges between 1% and 2% per year depending on the country.
RES	1% productivity growth per year. Limited land resource availability for new installation.	2% productivity growth per year. Limited land resource availability for new installation.
Resources extraction	Stable at 2020 levels.	Decrease by 10% per year after 2020.

Table 14 presents a summary of the shocks used for the energy system model under the same scenarios.

The implemented shocks are of a slightly different nature to reflect the specific capabilities of each model. The soft-linking procedure has allowed using these shocks in a wider modeling framework to produce a comprehensive evaluation of the BAU and the Decarbonization cases across the macroeconomic and the energy system model. The linking procedure aims at reaching convergence between the output that REMES-EU provides to GENeSYS-MOD in two subsequent iterations. The average percent variation of the solution by the REMES-EU CGE model from the previous iteration is computed considering y_{it} as the i-th element of the output vector from REMES-EU to GENeSYS-MOD at iteration t and setting up the measure ϵ_t as

$$\epsilon_t = \frac{\sum_{i=1}^{I} \mid \frac{y_{i,t} - y_{i,t-1}}{y_{i,t-1}} \mid}{I} \tag{2}$$

with I defining the length of the vector passed from REMES-EU to GENeSYS-MOD. By setting a threshold of 1% on the average results difference from the previous iteration, the linking has

***Table 14:* Translation of scenario features into quantitative input to the energy system model**

Shock	Bussines as Usual	Decarbonization
CO2 emissions	CO2 Prices obtained by the macroecoeconomic model.	CO2 Prices obtained by the macroecoeconomic model.
Technologies	Limited deployment of breakthrough technologies (no advanced hydrogen technologies, no CCS).	Advanced hydrogen technologies available.
RES	production price from RES set at 2020 level.	production price from RES decrease towards 2050.
Resources extraction	Set at existing phase-outs.	Set at existing phase-outs

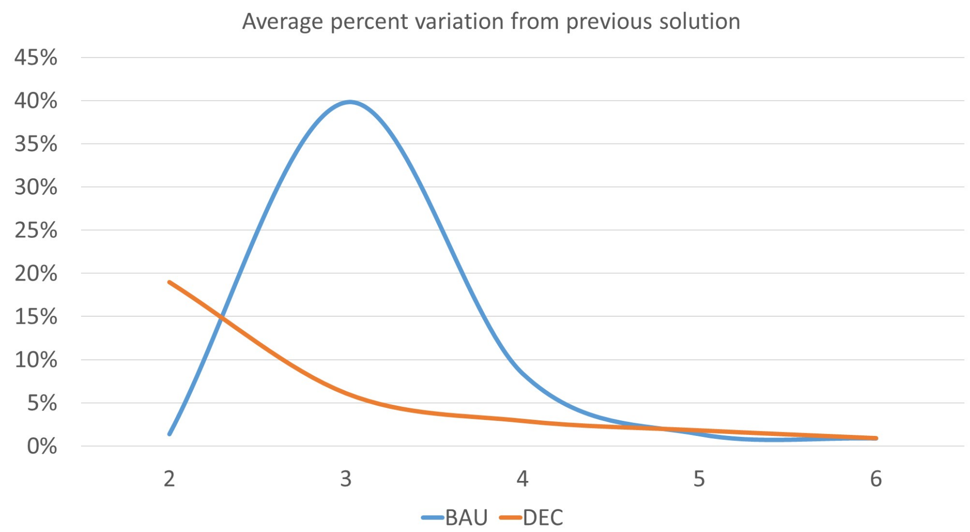

***Fig. 36:* Convergence of the linking procedure. The convergence parameter is calculated as the average percent variation from the previous solution in REMES-EU.**

been established after 6 iterations for both the cases analyzed by the common framework, as displayed in Figure 36.

The results of the common evaluations of the BAU and the decarbonization scenarios in the case of cooperation are displayed and discussed in the first part of the next section. The case of lack of cooperation has been analyzed by the macroeconomic model and its insights are reported in the second part of the next section.

6.3 A comparative analysis of the effects of the decarbonization

We will focus our analysis on the differences between the scenarios characterized by cooperation, then we will turn our attention to the scenarios without cooperation. The "point of first impact" of the decarbonization policy can be considered the decisions of both consumers and production sectors about the consumption bundle of energy carriers. We assume that energy efficiency follows nowadays trends in both scenarios. The effect of the growth on energy efficiency is coupled with the decrease in carbon budget availability, which under the BAU assumption is assumed to push towards a decrease of 60% of GHG emissions towards 2050, whereas it will be of 90% under the decarbonization scenario. We can see from Figure 37 that the power

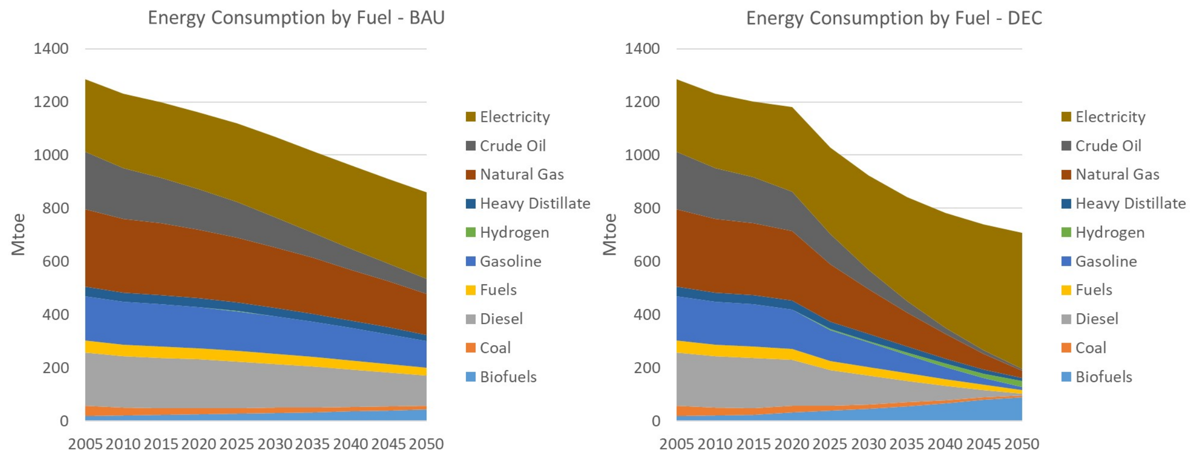

Fig. 37: **Energy consumption under BAU scenario (left) and decarbonization scenario (right). The figure shows a large overtake of demand of electricity and, in a smaller extent, biofuels and hydrogen under the DEC scenario.**

demand increases over time in both scenarios with the decarbonization scenario displaying a large overtake of electricity and, in a smaller extent, biofuels and hydrogen in the portfolio of energy carriers purchased in the considered countries. Under the BAU scenario, the power demand increase comes mostly from final consumption, while under the decarbonization scenario, the demand increase is also related to the larger requirements in industry and to the production of hydrogen from electrolysis. The electricity generation mix is shown in Figure 38, which displays how lower decarbonization requirements (BAU scenario) might allow the residual use of fossil sources such as hard coal in the generation mix while the use of other fuels is drastically reduced also in the BAU case. Under the decarbonization scenario, there is a clear technology switch with wind offshore becoming an important technology for electricity production and wind onshore and PV growing with much more intensity compared to the BAU scenario.

Figure 40 shows that emissions decrease in both scenarios with different intensities; we can notice that, under the decarbonization scenario, industry does not completely eliminate the emissions. This is due to its slower technology development compared to the speed at which the policy requires the system to cease using fossil fuels and adopt emission-free technologies. More specifically, the input from the bottom-up model shows that the industry does not completely eliminate the usage of some polluting energy sources such as hard coal as can be seen in Figure 39.

This has repercussions on the value that will be paid for the purchase of CO2 allowances and, ultimately, on their price, which will be around six times higher under the decarbonization scenario than under the BAU scenario, as can be seen in Figure 41.

The increase in price of the emission allowances reduces the sales of fossil fuels, whose prices decrease in both scenarios, as shown in Figure 42 for the case of Germany. While the BAU scenario displays a decrease in all prices[5], the decarbonization scenario shows that, in some cases, the prices initially increase and only after some years start decreasing. This happens for some types of fossil fuels whose usage is being reduced over time such as natural gas or heavy

[5] All prices are considered as inflation-adjusted. The price of biofuels is not included in the chart as its value increases much more than the other energy commodities.

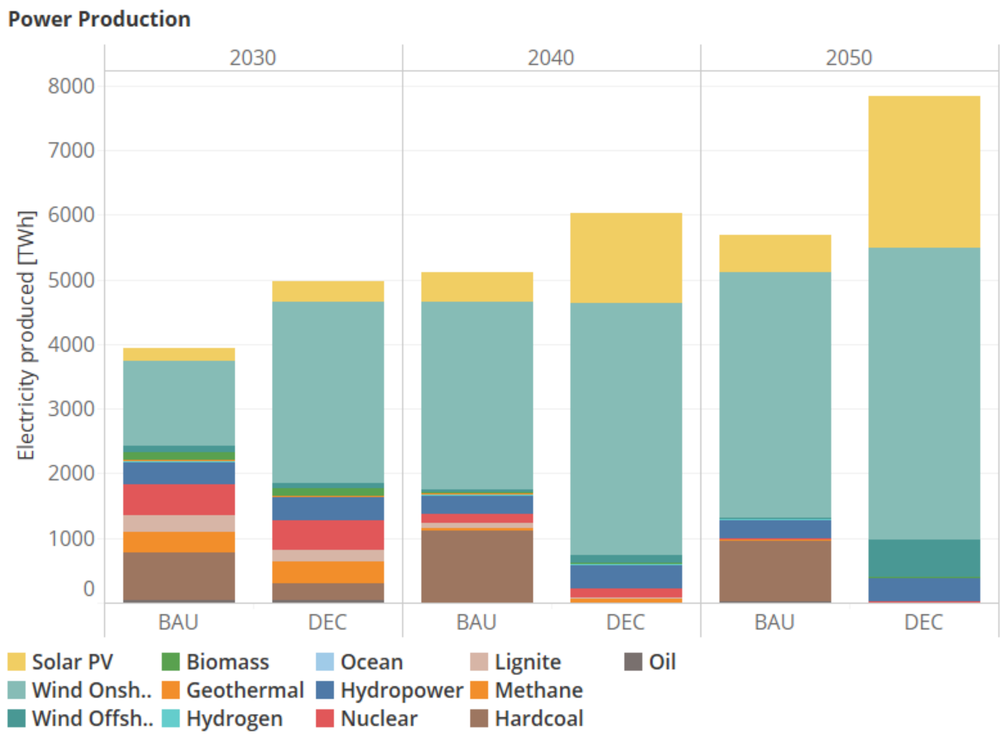

Fig. 38: **Energy mix for the electricity production under the considered scenarios. In the DEC scenario there is a large increase of production using Solar PV, as well as wind replacing hardcoal and nuclear.**

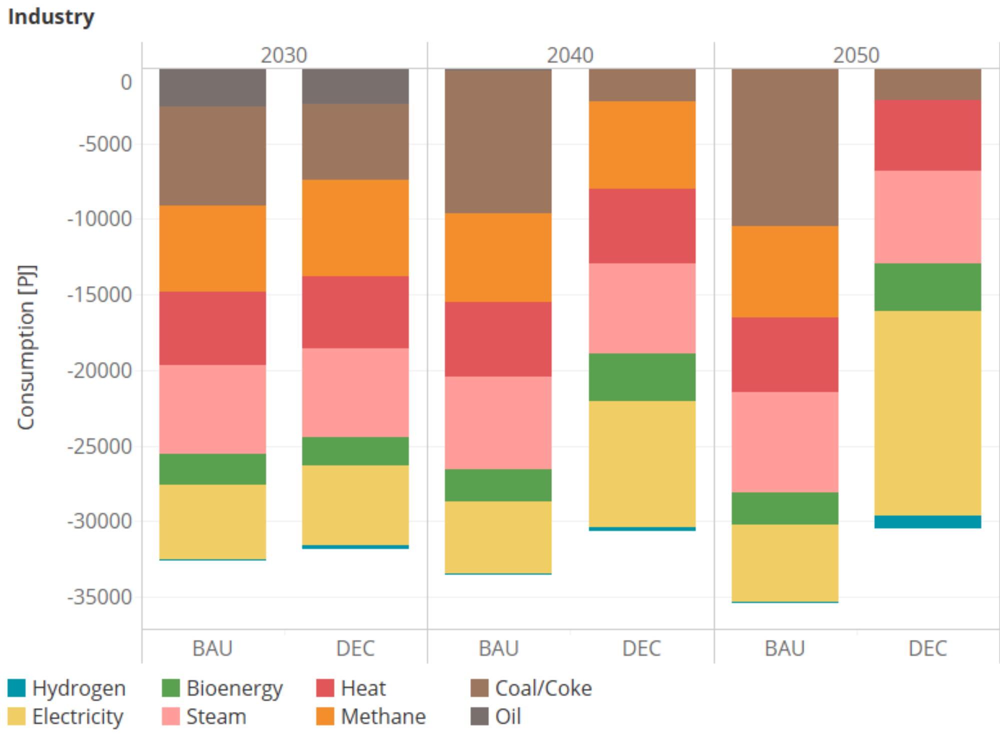

Fig. 39: **Energy consumption in Industry under the considered scenarios. Industry reduces energy consumption under DEC, also due to a reduction of its overall activity level.**

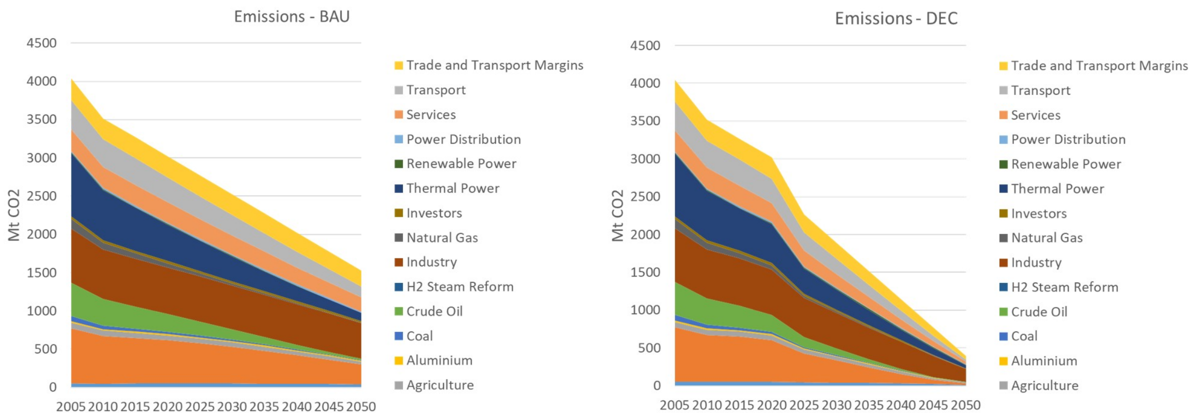

Fig. 40: **Emissions by sector under the BAU scenario (left) and decarbonization scenario (right). Emissions decrease in both scenarios with different intensities; under the DEC scenario, industry does not eliminate completely its emissions.**

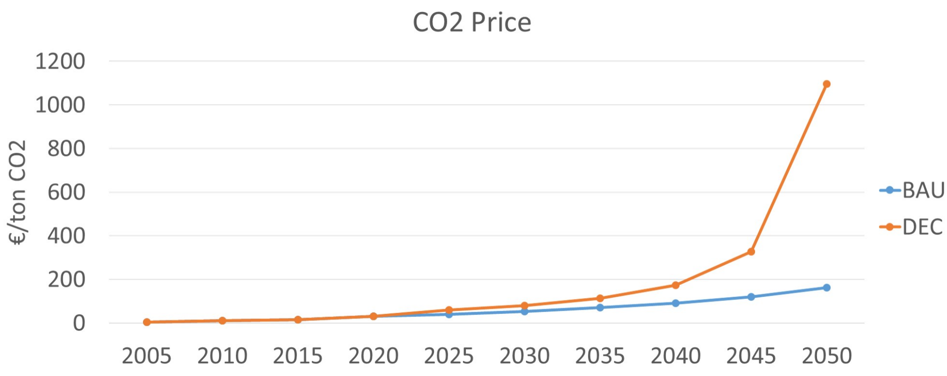

Fig. 41: **Price of CO2 allowances under the BAU scenario (left) and decarbonization scenario (right)**

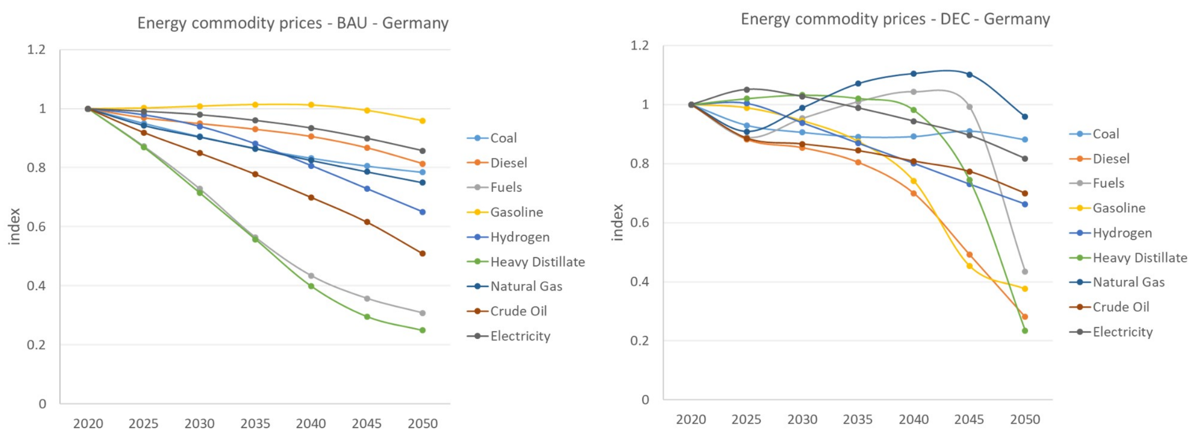

Fig. 42: **Evolution of energy commodities prices in Germany under the BAU scenario (left) and decarbonization scenario (right). Price of fossil fuels decrease due to their lower usage. In the DEC scenario some fossil fuel is still used in some sector until 2045, which makes the price only decrease when approaching 2050.**

distillate[6] which before reaching the 2050 decarbonization target are still used in industry as shown in Figure 39. In particular, the supply of natural gas under the decarbonization scenario is assumed to gradually decrease after 2025, while some production sectors still feature it until after 2040 (see Figure 39). The results obtained by the REMES-EU model suggest that most sectors transition towards biofuels and electricity. The growth rate of investments in renewables is quite high in the decarbonization scenario, due to the assumed increase in productivity and technology improvement on the supply side. This leads to a decrease in electricity prices towards 2050. The decrease in the purchase of fossil fuels has a strong impact on the activity level of the relative sectors, while sectors producing backstop commodities, such as hydrogen or the renewable power generation sectors are shown to increase activity levels under the decarbonization scenario. The sectors increasing their activity level compared to the BAU scenario are hydrogen production, which now operates on a commercial scale, electricity, and agriculture, which increases its activity

[6]Heavy distillate is still residually used in aluminum production until after 2040, while its production decreases gradually due to the decrease in oil extractions.

level to produce biofuels. The remaining sectors experience a decrease in value-added, mainly due to the increase in costs brought by the decarbonization requirements. These costs are directly connected to the speed of the transition of the technology towards a cleaner structure; the faster we can accommodate for the usage of clean energy sources, the lower will be the impact of decarbonization policies on the economic system. In the decarbonization scenario, the residual amount of fossil fuels in the production system, due to lagging technology development, contributes to increasing production costs. This leads to a decrease in demand for manufactured goods and to a consequent decrease in value added for the sector. Moreover, the higher energy costs also contribute to a reduction of demand for capital, labor, and materials and in a general reduction of the industrial activity level. The European GDP breakdown by sector in Europe as well as the overall effects of the decarbonization scenario on value-added can be seen in Figure 43. We have removed the percentage difference related to hydrogen sectors as the value is much higher than the typical values taken by the other sectors albeit contributing only marginally to the formation of the overall GDP. It is easy to see that the largest contributors to the European GDP are services and industry, with a smaller contribution from the transport, agriculture, and oil sectors and a residual contribution from the other sectors such as power generation and transmission. In the decarbonization scenario, the value added brought by sectors based on fossil extraction and refinery is replaced mainly by sectors for generation of power from renewable sources and by agriculture, which provides biofuels. From the upper chart in Figure 43, it can be noticed that, besides sectors producing clean energy, the decarbonization process, not supported by other changes in technology such as improvements in energy efficiency or societal changes such as shifts in consumption preferences is expected to lead to a general decrease in value added. As a consequence, the economy is expected to grow less under the decarbonization scenario. The contraction of the growth is particularly strong towards the approach of 2050 when the CO2 cap becomes more stringent. Figure 44 shows the development of the GDP under the considered scenarios.

In the decarbonization scenario, several sectors go through an increase in costs for energy due to the need for purchasing CO2 allowances, as well as for the need to transition to the usage of clean energy commodities[7]. Agriculture experiences a high increase in energy costs due to the fact that biofuels, one of the commodities experiencing the highest increase in price under the decarbonization scenario, are used intensively in this sector. The agricultural sector is also the one producing biofuels, which become a source of extra profits. Nevertheless, the agricultural sector needs to keep using the land to produce crops, which limits the availability of land for biofuels. This, joint with the increase in demand for such a commodity, increase its price. Other sectors such as services, industry, and transport see a high increase in costs for energy purchases as well. Nevertheless, services manage to reduce the purchases of energy in exchange for more intensive use of labor and, to a smaller extent, of capital. Industry tries to cover for the increased price of energy by reducing the amount purchases of other factors without drastically reducing the amount of energy, but rather moving towards different energy sources such as electricity and biofuels. Finally, transport decreases the purchase of all the production inputs in conjunction with the reduction of energy purchases. These different behaviors lead to different impacts on the decrease in profitability of these sectors. Mainly, services manage to only lose 8% of its value-added compared to the BAU scenario in 2050, while industry experiences a loss of 16% in value-added and transport loses 10% of the value added compared to the BAU scenario in 2050.

[7]Notice that while electricity prices decrease under the decarbonization scenario, the price for hydrogen and biofuels are increasing.

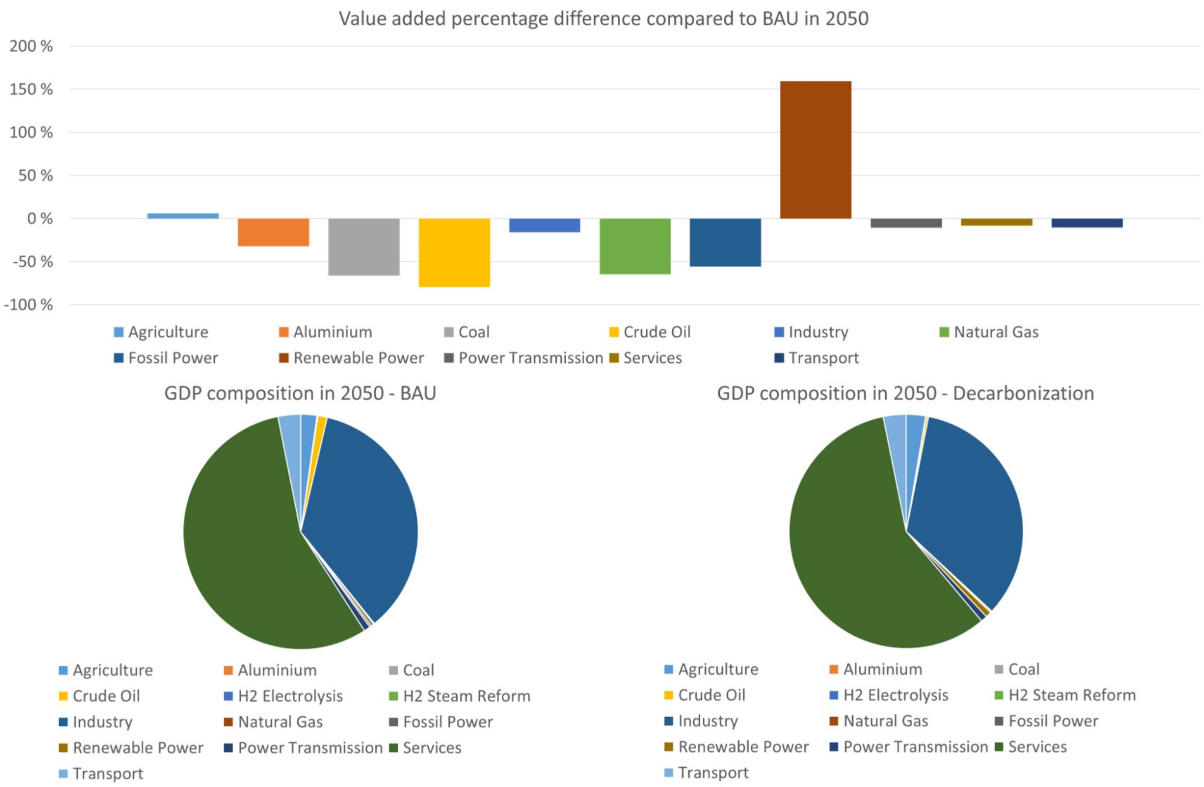

***Fig. 43:* Value added for the economic sectors in 2050 under the considered scenarios**

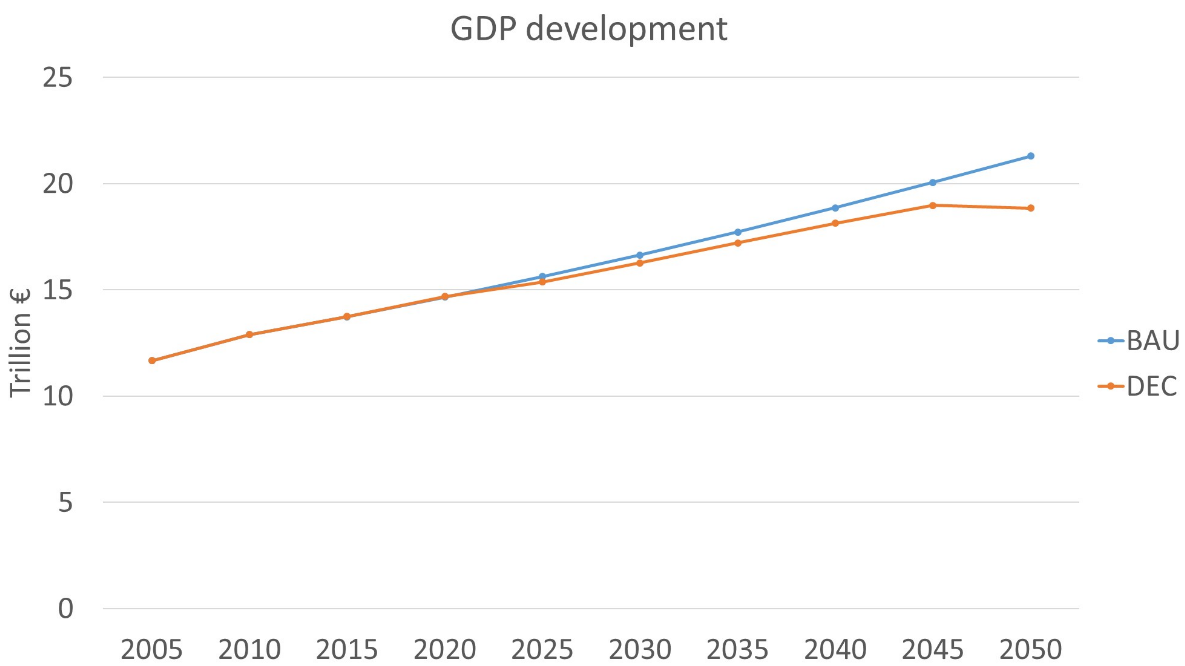

***Fig. 44:* European GDP development under the considered scenarios**

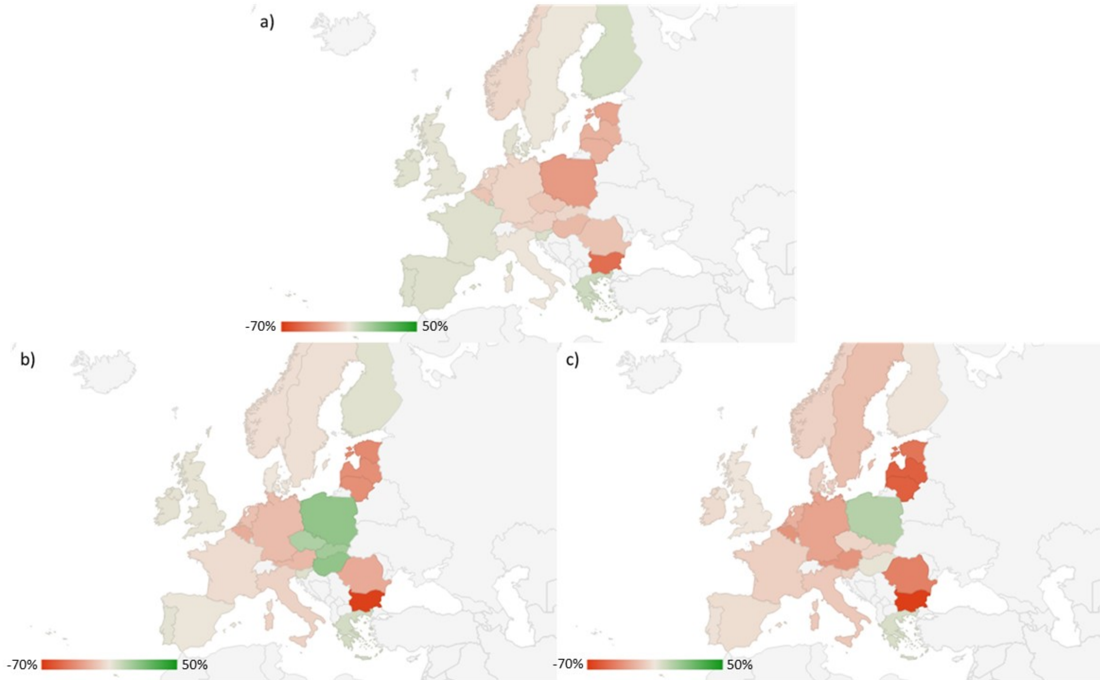

Fig. 45: **Country specific GDP deviation compared to BAU in 2050 in case of a) decarbonization under cooperation, b) decarbonization with Visegrad countries calling off the agreements and c) decarbonization with Visegrad countries calling off the agreements but subject to tariffs for exports**

In general, the increase in prices for commodities in the energy nest of various sectors leads to a general reduction of value-added and GDP in the decarbonization scenario compared to the BAU scenario. This can be seen with more detail in Figures 43 and 44. Without additional policies or technological improvements, the GDP in 2050 will be the level of the one in 2040.

We now briefly focus on the decarbonization scenario under the non-cooperative case. In particular, we assume that some of the EU countries - Slovakia, Czech Republic, Hungary, and Poland - (in this case we have selected the Visegrad countries as an exemplification case) choose to call off the green transition agreements and not limit their emissions. The rest of the EU can respond by assuming that the carbon footprint of the production of such countries is higher compared to the one coming from countries that have implemented a decarbonization policy. Thus, the EU countries might discourage trade with those exiting countries by defining a tariff that would drastically reduce imports from the countries calling off the decarbonization agreements. Figure 45(a) shows that the decarbonization policy through the introduction of CO2 allowances with a gradually decreasing carbon cap leads to a decrease in GDP in several European countries, with a particularly high impact on the eastern group, with Poland suffering particularly due to the phase off of the coal sector and Bulgaria due to the rigidities of the industrial structure. In (b) we see the potential effect on GDP of the Visegrad countries calling off the decarbonization agreements. Namely, Hungary, Poland, Slovakia, and the Czech Republic would experience a quite high increase in GDP compared to the BAU scenario. This is both due to smaller production costs for energy consumption and for the increase in exports to countries experiencing an increase in costs due to the energy transition process. The remaining European countries engaging in the collaborative effort for decarbonizing their systems will need to place a higher effort to make up for the missed commitment from the exiting countries in terms of decarbonization and might therefore end up with a slight further reduction in GDP. On the other hand, the rest of Europe might respond to these policies by reducing the imports from the Visegrad countries by levying tariffs for the imported goods that reach 100% of the initial price of the imported good. The effect of the application of tariffs for imports from the Visegrad countries is displayed in Figure 45(c). What is noticeable is that with the introduction of tariffs on imports of goods from the Visegrad countries to Europe, most of the Visegrad countries go back to a growth similar to the one experienced under the decarbonization case with cooperation besides for Poland, which still grows but with lower intensity thanks to its continued exploitation of coal mines to produce low-cost electricity and use to support an industrial system that can keep exporting to extra EU countries. What is interesting to notice is that the remaining EU countries are worse off compared to the case without tariffs. This is due to the fact that Visegrad countries were providing low-cost intermediate products which were useful to decrease the production costs for the industries located in the rest of Europe. Moreover, the residual amount of fossil fuels in Europe was still sold to Visegrad countries, leading both to increased revenues from fossil fuels and a reduction of production costs for the EU countries that were engaging in the cooperative decarbonization effort. This example shows how using retaliation measures such as tariffs leads to a degradation of the economic conditions of both the target and the implementer of such measures when it comes to decarbonization policies.

7 Appendix

7.1 e3value methodology

The *e3value* methodology allows conceptualizing a business case by constructing a value model, representing it graphically in a rigorous and structured way, and performing a financial sensitivity analysis of the case at hand (see [111] for details). In particular, the *e3value* methodology provides modeling concepts for showing which parties exchange things of *economic* value with whom and expect what in return. The methodology has been previously applied in a series of industries including media, banking insurance, and telecommunication to design value models of networked organizations. Especially, cases in the telecommunication industry show similarities with the electricity sector with respect to re-regulation. Brief description concepts of the *e3value* methodology using an educational example is presented in Figure 46.

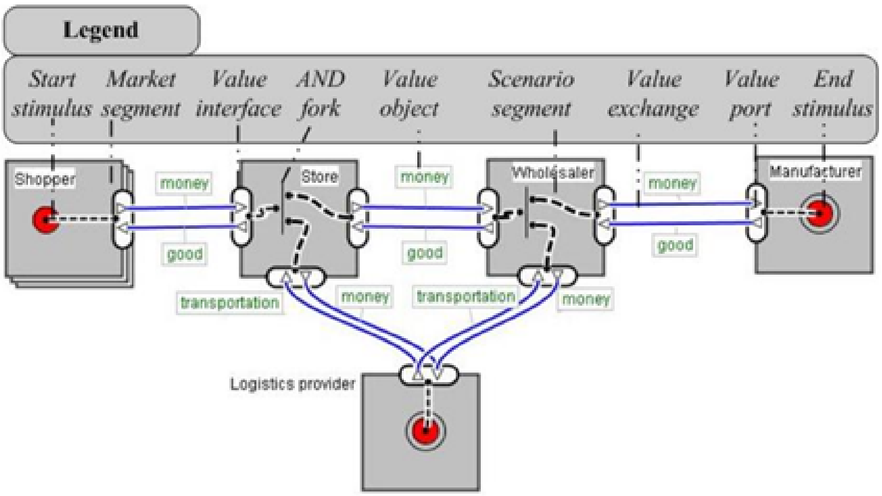

***Fig. 46:* Example and Legend: A shopper obtains a good from a store and offers money in return. So do the other actors. Source:[41]**

The method is based on the Unified Modeling Language (UML) and has several similarities with Use Case (UC) methodology but focuses on rather economic aspect as value creation and exchange as well as profitability analysis, rather than technical requirements.

e3value ontology

Actor: An actor is perceived by its environment as an independent economic (and often also legal) entity. An actor makes a profit or increases its utility. In a sound, sustainable, business model each actor should be capable of making a profit. The example shows several actors: a store, a wholesaler, a logistics provider, and a manufacturer.

Value Object: Actors exchange value objects, which are services, products, money, or even consumer experiences. The important point here is that a value object is of value for one or more actors. Goods and money are examples of value objects, but transportation service is also a value object.

Value Port: An actor uses a value port to show its environment that it wants to provide or request value objects. The concept of port enables us to abstract away from the internal business processes, and to focus only on how external actors and other components of the business model can be plugged in.

Value Offering: A value offering models what an actor offers to or requests from his/her environment. The closely related concept value interface (see below) models an offering to the actor's environment and the reciprocal incoming offering, while the value offering models a set of equally directed value ports exchanging value ports. It is used to model e.g. bundling: the situation that some objects are only of value in combination for an actor.

Value Interface: Actors have one or more value interfaces, grouping individual value offerings. A value interface shows the value object an actor is willing to exchange in return for another value object via its ports. The exchange of value objects is atomic at the level of the value interface.

Value Exchange: A value exchange is used to connect two value ports with each other. It represents one or more potential trades of value objects between value ports.

Market Segment: The concept market segment shows a set of actors that for one or more of their value interfaces, value objects equally from an economic perspective. A shopper is an example of a market segment. Here we assume that all (implicit) actors in the shoppers' segment value obtained and delivered objects in the same way. Naturally, this is a simplification of the real world, but choosing the right simplifications is exactly what modeling is about.

The concepts above allow us to model who wants to do business with whom but cannot represent all value exchanges needed to satisfy a particular end consumer need. It occurs often that, to satisfy an end consumer need, several other actors must exchange objects of value with each other. As an example, think of a store that exchanges economic values with an end consumer: as a result, the store must also exchange values with a wholesaler. It is our experience that showing all such value exchanges to satisfy an end consumer need contributes largely to a common understanding of an e-business idea. To that purpose, we use an existing scenario technique called Use Case Maps, which show which value exchanges should occur as a result of a consumer need (which we call a start stimulus), or as a result of other value exchanges. Below, the main UCM modeling constructs are briefly discussed.

Scenario Path: A scenario path consists of one or more scenario segments, related by connection elements and start/stop stimuli. A path indicates via which value interfaces objects of value must be exchanged, as a result of a start stimulus, or as a result of exchanges via other value interfaces.

Stimulus: A scenario path starts with a start stimulus, which represents a consumer need (in the example the need for a specific good). The last segment(s) of a scenario path is connected to a stop stimulus. A stop stimulus indicates that the scenario path ends.

Scenario Segment: A scenario path has one or more segments. Segments are used to relate value interfaces with each other (e.g. via connection elements) to show that an exchange on one value interface causes an exchange on another value interface.

Connection Element: Connections are used to relate individual scenario segments. An **AND** fork splits a scenario path into two or more sub-paths, while the **AND** join collapses sub-paths into a single path. An **OR** fork models a continuation of the scenario path into one direction that is to be chosen from a number of alternatives. The **OR** join merges two or more paths into one path. Finally, a value interface itself is seen as a connection element, so it is for instance possible to connect two value interfaces by a scenario segment.

Steps in the e3value methodology

Step 1 – Business idea description: Write down a short business case description to express the business idea. The value model is a representation of the real world and, hence, such representation cannot include all the objects of the real world, but the basic rule is to include all involved actors and activities in the value model process.

Step 2 – Goal selection: The first consideration to be taken when modeling the business is specifying all the goals that stakeholders want to satisfy with that business, even if they may be in conflict with the goals of another stakeholder(s).

Step 3 – Technology selection: Once the goals are identified, the next step is to select an appropriate technology to achieve both operational (short-term) and strategic (long-term) goals.

Step 4 – Value activity selection: In this step, value activities to be included in the model are selected.

Step 5 – Value interface selection: In this step, all value interfaces necessary to model the business case are selected from a library of interfaces, where general and optional interfaces are provided for each activity.

Step 6 – Ports connection: The value interfaces must be connected to obtain a connected value model.

Step 7 – Actor selection: Each activity should be performed by an actor, but this is not a strict one-to-one relation. Some actors perform more than one activity, and in some cases, an activity should be divided between two actors.

Step 8 – Scenario path identification: A scenario path is used to explain cause-effect relationships by traveling over paths through a system. Scenario paths allow counting the number of value exchanges in a given time period, which is very important to perform the profitability analysis.

Step 9 – Information system model construction: Once a correct value model has been constructed, the information system needed to support such a model must be addressed. This step is performed only when the expenses to maintain such an information system are substantial; otherwise, they will be included as OM costs.

Step 10 – Base-line profitability sheets calculation: The evaluation of a business model focuses on the question of whether it is feasible from an economic point of view and whether a scenario is profitable for each actor involved in the value model. The impact of the business model on the different actors is assessed by creating profitability sheets for each actor involved, where economic value is assigned to objects delivered and received.

Step 11 – Sensitivity analysis: Since it is not possible to predict the future, the important result of the analysis is not the numbers on profitability themselves, but the reasons behind them. Therefore, a sensitivity analysis is very useful to check the robustness of the results obtained when different assumptions are taken.

Step 12 – Investment analysis: After a scenario is chosen, a detailed analysis of financial aspects must be made. There are several standard criteria for investment analysis (e.g. NPV and IRR).

7.2 Glossary of terms and definitions for the business dimension

- **Active Customer** - a final customer, or a group of jointly acting final customers, who consume, or stores electricity generated within its premises located within confined boundaries or, where permitted by a Member State, within other premises, or who sells self-generated electricity or participates in flexibility or energy efficiency schemes, provided that those activities do not constitute its primary commercial or professional activity. **Source:** Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU

- **Citizen Energy Community (CEC)** - a legal entity that: (a)is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises (b)has for its primary purpose to provide environmental, economic, or social community benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits; and (c)may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services, or charging services for electric vehicles or provide other energy services to its members or shareholders. **Source:** Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU

- **Closed Distribution System (CDS)** - a distribution system, which distributes electricity within a geographically confined industrial, commercial or shared services site and does not supply household customers, without prejudice to incidental use by a small number of households located within the area served by the system and with employment or similar associations. **Source:** European Commission, Commission Regulation (EU) 2016/1388 of 17 August 2016 establishing a Network Code on Demand Connection

- **Demand Response (DR)** - the change of electricity load by final customers from their normal or current consumption patterns in response to market signals, including in response to time-variable electricity prices or incentive payments, or in response to the acceptance of the final customer's bid to sell demand reduction or increase at a price in an organized market. **Source:** Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU

- **Energy Carrier** - either a substance or a phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes. **Source:** ISO13600 (Technical energy systems — Basic concepts)

- **Energy Vector** - a tool that allows the transportation and/or storage of energy is called energy vector. An energy vector allows transferring, in space and time, a quantity of energy. **Source:** Orecchini F. The era of energy vectors. Int J Hydrogen Energy 2006;31(14):1951–4.

- **Guarantee of Origin** - an electronic document that has the sole function of providing evidence to a final customer that a given share or quantity of energy was produced from renewable sources. **Source:** Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources.

- **Web-of-Cells** - a portion of the power grid able to maintain an agreed power exchange at its boundaries by using the internal flexibility of any type available from flexible generators/loads and/or storage systems. The total amount of internal flexibility in each cell shall be at least enough to compensate for the cell generation and load uncertainties in normal operation. The Cell is not a microgrid and does not have to be energy self-sufficient or able to operate in islanded mode. **Source:** FP7 project ELECTRA IRP, "The Web-of Cells Concept - an architecture for decentralized balancing and voltage control in the future power system," ELECTRA Consortium, 2018.

7.3 Publications and dissemination

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- Thorsten Burandt, Paolo Pisciella, and Pedro Crespo del Granado. *Cooperation in the European Energy Transition: Impacts to the Economy and the Role of Carbon Price Policies.* Energy, COVID, and Climate Change, 1st IAEE Online Conference, June 7-9, 2021. International Association for Energy Economics, 2021.
- Andrei Morch, Sarah Schmidt and Pedro Crespo Del Granado, *Identification of barriers and investment determinants for hydrogen infrastructure: Development of new business models*, 2022 18th International Conference on the European Energy Market (EEM), 2022, pp. 1-6, doi: 10.1109/EEM54602.2022.9921163.
- Backe, Stian, Sebastian Zwickl-Bernhard, Daniel Schwabeneder, Hans Auer, Magnus Korpås, and Asgeir Tomasgard. "Impact of energy communities on the European electricity and heating system decarbonization pathway: Comparing local and global flexibility responses." Applied Energy 323 (2022): 119470.
- Thorsten Burandt, Ruud Egging, and Pedro Crespo del Granado. *Natural Gas in the European Energy Transition: stranded assets or cost-effective flexibility?* . Working Paper (Submitted to an International Journal), 2022

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