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Is there a role for liquid fuels in future low-carbon energy systems? – A continuous interaction between global energy systems modeling and local energy port cluster participation

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HIGHLIGHTS

- Liquid fuels will have a role in future low-carbon energy systems.
- Main sectors for liquid fuels include aviation and industrial feedstock.
- Biofuels and electrofuels share depend on the socio-economic narrative.
- The global role of liquid fuels aligns with local low-carbon initiatives at ports.
- Insights strengthened by combining energy systems model and stakeholder participation.

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ABSTRACT

Low-carbon transition is a focus in current energy debates. Given current reliance on liquid fuels, this transition raises uncertainties regarding their future role. This study investigates liquid fuels' future role by complementing a global Energy Systems Optimization Model (ESOM) with stakeholders' engagement from a Swedish local energy port cluster. Stakeholders' participation followed a three-phase process: semi-structured interviews and two workshops. The model examined how liquid fuels may evolve from 2020 to 2070 across different socio-economic narratives. While stakeholders acknowledged their commitment to contribute to a low-carbon energy transition, they expressed uncertainty about the future role of today's infrastructure. Nonetheless, stakeholders anticipated continued demand for liquid fuels, confirmed by local low-carbon initiatives, presented as market and policy-driven. Similarly, model results indicate continued demand for liquid fuels, particularly in hard-to-abate sectors such as aviation and industrial feedstock. Yet, the cost-effective role of liquid fuels depends on socio-economic scenarios, carbon budget, carbon storage capacity, biomass availability, and interregional trade. Through a single analytical framework, this study contributes to the ESOM community by showing how a dialogue between energy modelers and local actors can be mutually beneficial, i.e., actors can help refine modeling uncertainties, and model results can guide local actors towards low-carbon transitions.

1. Introduction

1.1. Motivation

Several nations have made efforts in recent years towards a low-carbon transition, including reduced use of crude oil-based fuels in various sectors [1]. Still, by 2022, crude oil-based fuels accounted for 30% of the total global energy supply [2], representing the second largest contributor of greenhouse gas (GHG) emissions from fuel combustion, after coal, with a share of 33% [3].

While some sectors shift away from fossil fuels through increasing electrification based on renewable sources, other sectors keep

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maintaining a high dependence on crude oil-based fuels (see e.g., [4]). These sectors, often described as hard-to-abate sectors (long-distance transport segments – e.g., aviation and shipping – and industrial feedstock), are characterized by (i) international standards; (ii) high energy density fuels, (iii) technical complexity; and (iv) multiple stakeholders' involvement [5].

In this study, liquid fuels include all fuels that, under ambient conditions and in a liquid form, store usable energy that can be transported to a desired location, enabling the energy to be harnessed for performing work, generating heat, or producing electricity. Liquid fuels can be divided into crude oil-based fuels and synthetic fuels. Synthetic liquid fuels are in this study regarded as all liquid fuels not originating from the refining of crude oil. Depending on their production pathway (i.e., carbon atom origin), synthetic liquid fuels can be regarded as fossil-based or non-fossil-based [6]. The latter liquid fuels can be either biofuels (i.e., depending on biogenic carbon) or electrofuels (i.e., defined in this study as fuels based on hydrogen from water electrolysis combined with carbon atoms). Overall, synthetic liquid fuels offer relatively high energy density and compatibility with existing infrastructure for transport, distribution, and storage of energy carriers [7]. Thus, synthetic liquid fuels may be good candidates for the low-carbon transition of hard-to-abate sectors.

1.2. State of knowledge

Depending on the level of carbon budget stringency, Byers et al. [8], by using a global integrated assessment model (IAM) suggest that liquid fuels could supply between 18% and 33% of global final energy demand by 2070, corresponding to temperature outcomes below 1.5 °C and above 2 °C, respectively. Although IAMs successfully integrate energy, land use, climate, and economic systems to explore long-term mitigation pathways, they often lack sufficient technological detail [9]. In the context of this study, IAMs generally represent carbon capture and utilization (CCU) routes in a simplified way, limiting their ability to capture the role of synthetic fuels fully [10]. Such dimensions can be fairly captured by Energy Systems Optimization Models (ESOMs), according to which the role of synthetic liquid fuels for a low-carbon transition in different parts of the energy system is already being discussed (e.g., in transport systems [11–33] as well as in other energy sectors, e.g., electricity, heating, industrial feedstock, and agricultural fertilizers [12–14,16,17,22,25,26,28,30–33]). The referenced studies highlight the flexible role that synthetic liquid fuels can play across various parts of the energy system, from a cost-effective perspective. Furthermore, these studies tend to agree that these fuels can serve both as inputs for different energy processes and as tools to enhance energy system flexibility.

Such flexibility is linked to several key characteristics of synthetic liquid fuels, i.e., (i) compatibility with existing infrastructure; (ii) ability to enable sector coupling; (iii) tradability across regions and markets; and (iv) suitability for use in hard-to-abate sectors. Moreover, in the specific case of electrofuels, due to the flexible operation of electrolyzers, synthetic liquid fuels can effectively balance the intermittency caused by the growing share of variable renewable energy sources in the electricity sector. The existing literature, further, highlights that production pathways for synthetic liquid fuels – biofuels and electrofuels – and their applicability – global [12,15,21,28], continental [14,22,25,29,32] and national [11,13,16–20,23,24,26,27,30,31,33] –, might depend on geographical aspects.

Focusing on a Dutch national case study, Okken and Doorn [11], pioneers of applying energy systems models for testing different maximum carbon dioxide (CO_2) emission rates, argue that liquid biofuels are only cost-effective at severe CO_2 constraints. Grahn et al. [12] assess a global perspective using the ESOMs GET v1.0 and BEAP, analyzing why the latter finds biofuels for transport a cost-effective solution, whereas the former does not. The main reason is that GET v1.0 includes other low-carbon technology options (i.e. hydrogen), whereas no other low-carbon option apart from biofuels is allowed for transport in the BEAP model. Years later, Martinsen et al. [13], who apply an ESOM, IKARUS model, to a German national case study, find that liquid biofuels only become preferable transport energy carriers under strict regulatory (i.e., strict carbon budgets) and market-based (i.e., high CO_2 taxes) incentives.

In more recent studies, the role of synthetic liquid fuels under strict carbon budgets is further discussed by continuously improving the techno-economic coverage of ESOMs. As such, Blanco et al. [14], while recognizing electrofuels as a versatile low-carbon energy carrier, assess the potential enablers and barriers these fuels might face. Using a bottom-up cost-optimization modeling exercise at the European level and across different energy sectors, the authors argue that electrofuels become cost-effective primarily under conditions of limited carbon capture and storage (CCS) availability, low biomass potential, and cost reductions for components of their production supply chain. Similarly, Lehtveer et al. [15] analyze the role that electrofuels might play in a low-carbon transport sector at a global level. Through cost-optimization modeling, the study argues that under tight carbon budgets, bioenergy with CCS (BECCS) is found to be more cost-effective than reusing carbon. Accordingly, electrofuels are found to play a limited role in the future transport sector unless CCS is unavailable, biomass is scarce, or stricter climate policies increase energy costs. Relying on the results of an ESOM applied to the Nordic Countries, Mustapha et al. [16] expand a cross-sectoral perspective under different levels of biomass scarcity. According to a cost-optimization perspective, the study finds that, under low availability of biomass, liquid biofuel is found more cost-effective than the use of solid biomass in power and heat sectors.

Bramstoft et al. [17] evaluate how locally available sustainable biomass can be converted into synthetic gaseous and liquid fuels through various production pathways (i.e., biofuels and electrofuels) and within an integrated energy sector assessment, using Denmark as a case study for 2050. The study optimizes the production of geographically distributed biomass resources and synthetic liquid fuels, while considering system-wide energy synergies. Bramstoft et al. [17] conclude that methanol, produced as both a biofuel and electrofuel, serves as a good proxy for a cost-effective synthetic liquid fuel, with significant applicability for the heavy road transport segment, shipping, and agricultural fertilizers. Lester et al. [18], through a linear optimization model, examine the low-carbon transition of the Nordic and German transport systems. The study argues that synthetic liquid fuels, produced from feeding in hydrogen to biofuel production facilities to react with excess CO_2, so-called bio-electrofuels, are likely to play a central role in the defossilization of the transport sector. Nonetheless, the cost-effectiveness of synthetic liquid fuels' production pathways is found to depend on the availability of biomass, the share and prices of renewable electricity, and fuel demand among different transport segments, as well as other energy sectors.

Drünert et al. [19] evaluate the potential of electrofuels for aviation, highlighting their advantage as drop-in, low-carbon alternatives, but also stressing their high costs, low conversion efficiency, and strong dependence on renewable electricity and CO_2 sources. Using a bottom-up techno-economic assessment for Germany, the authors model different production pathways and resource requirements to identify key cost and feasibility drivers. They conclude that electrofuels play a role in aviation's low-carbon transition, only if renewable energy, CO_2 capture, and synthesis technologies achieve substantial cost reductions and scale. Millinger et al. [20] discuss the potential of electrofuels as demand-side management strategies for benefiting from excess renewable electricity. Applying an ESOM to a German national case study, Millinger et al. [20] find that CCU is more cost-effective than CCS technologies, as it benefits electrofuels production, which by itself provides an ancillary benefit to the energy system, by avoiding curtailment. Brynolf et al. [21] examine the potential of different types of electrofuels to decarbonize the transport sector, including road, shipping, and aviation, with a global perspective. They conclude that bio-electrofuels are more cost-effective than other types of electrofuels. Nonetheless, Brynolf et al. [21] further reflect that the low technology maturity of electrofuels raises many uncertainties that could dictate the future of these liquid fuels, such as competing alternative fuels, the availability of renewable electricity and biomass, carbon capture (CC) deployment, and policy and regulatory support [22].

Wassermann et al. [23], using a cost-optimization model, investigate the techno-economic feasibility of aviation electrofuels in Germany, focusing on production and supply costs under different conditions. The authors analyze how variables such as electricity price, plant size, and CO_2 sourcing affect cost outcomes and find that while electrofuels can technically supply aviation demand, their competitiveness depends strongly on cheap renewable electricity and cost reductions along the production chain. Zhao et al. [24] explores how the Chinese transport sector might evolve under strict carbon budgets. By applying a cost-optimization rationale, the study argues that if Chinese oil-based transport demand is met by low-carbon synthetic fuels, GHG emissions can decrease up to 93%. Yet, such potential is mainly based on an electrofuel route, becoming quite volatile to the different techno-economic aspects of the green hydrogen supply chain. Such an outcome is further discussed by Victoria et al. [25] and Jordan et al. [26]. These two ESOMs studies acknowledge that electrofuels gain especially traction under limited CCS and biomass availability, an approach tested at the European and German levels, respectively.

Aliabadi et al. [27] and Mignone et al. [28] show that both biofuels and electrofuels are important energy carriers, especially when targeting hard-to-abate sectors, both in a national and global perspective. From a cost-optimization perspective, the authors highlight a correlation between biofuels and electrofuels, meaning that constrained availability of one of these energy carriers implies that the energy system tends to rely more heavily on the other, and vice versa. Expanding on this correlation, Chyong et al. [29] and Wulff et al. [30] refer to that European and German electrofuel demand is primarily set by biomass availability, but also by the strictness of carbon budgets. Under constrained biomass availability, the latter two studies argue that the system may, from a cost-optimization perspective, favor biofuels over electrofuels. This is especially the case under stricter carbon budgets, as electrofuels production may compete with CO_2 sequestration.

According to a cross-sectoral perspective, Law et al. [31] and Millinger et al. [32] complement the above discussion by testing a cost-optimal allocation of biomass. By applying ESOMs, the two studies argue that biogenic carbon is more valuable as both storage and electrofuel feedstock than producing liquid biofuels. As tested by Catania et al. [33], such a rationale is especially valid under national tight carbon budgets, adding pressure to transport systems, and hence anticipating an increase in electrofuels demand.

Nevertheless, the above-mentioned ESOMs studies tend to have relatively narrow approaches, i.e., exclusively focusing on (i) a specific synthetic liquid fuels production pathway; (ii) a specific synthetic liquid fuel type; (iii) a specific segment of the energy sectors; or (iv) modeling synthetic liquid fuels as an aggregated and exogenous demand, dismissing a representation of the different end-users. Thus, there is a lack of a comprehensive approach to assess the role of these fuels. Similarly, existing studies often fail to analyze the effect that different socio-economic trends may have on the role of synthetic liquid fuels.

Yet, such socio-economic trends – typically conceptualized through the Shared Socioeconomic Pathways (SSPs) framework [34] – can evolve in diverging directions, each carrying different implications for future energy systems. Acknowledging the shaping role of socio-economic developments, different authors seem to agree in assessing low-carbon transitions as being context-dependent (see e.g. [35–40]). Thereby, the role of synthetic liquid fuels might also vary across different regions of the world, as an outcome of different socio-economic trends and energy profiles. Analyzing the future role of these fuels as being context-dependent is suggested to benefit from adding stakeholders' participation, as a qualitative tool, to a typically quantitative analysis. Such an add-in will act as a key provider of local context understanding, and thus (i) help actors to translate their conceptual goals into feasible plans [41]; (ii) improve the credibility and transparency of quantitative analysis outcomes [42]; and (iii) support legitimate decision-making [43].

Presently, around 64% of oil produced globally is moved by ships [44]. Thus, a thorough analysis of the future role of synthetic liquid fuels might consider how ports, as key stakeholders in handling liquid fuels, will adapt their operations to a low-carbon transition in response to changes in the type and volume of traded substances. Typically, ports, in this study referred to as local energy port clusters, operate at a key interface between land and sea. As local energy clusters, ports host diverse industries such as maritime transport, oil and gas refineries, cruise tourism, heavy road transport, bulk transfer, manufacturing, electricity generation, electricity grid operations, energy storage, and offshore wind energy [45]. Due to their strategic position, ports have been suggested as potential future energy hubs where fossil-free fuels can be produced, stored, traded, and distributed [45,46].

Depicting the role that energy port clusters play towards a low-carbon transition calls for understanding how the relevant companies, currently holding a fossil fuel-based economy (e.g., crude oil and gas refineries), linked to the cluster, will evolve in the future. The future low-carbon business models of ports, and specifically their confined crude oil and gas industries, have been analyzed in previous research [47–52]. Gondal and Masood [47] suggest that shifting gas refineries' fossil-based operation dynamics can benefit from using power-to-gas technologies to convert excess renewable energy towards synthetic natural gas production. This change in dynamics will not only hasten a low-carbon transition but will also ensure more efficient use of decommissioned oil infrastructure and lower energy costs. Pickl [48] also discusses an existing link between companies' crude oil and gas reserves and their renewable adoption. On this note, the author argues that companies with low fossil reserves face a smoother and faster low-carbon transition.

Molavi et al. [49] examine how regulations, incentives, and tax policies can steer not only ports but also their confined oil- and gas-based industries towards a low-carbon transition. They emphasize that shifting today's fossil fuel–dependent port systems require solutions that balance emission reductions with overall cost. The study argues that no single measure will suffice; instead, a combination of market-based and policy-driven strategies is necessary. Furthermore, Green et al. [50] investigate how business models of crude oil and gas industries have been developing in response to set climate goals. They find that despite the efforts of the involved stakeholders, the dynamics of these industries face high inertia towards a low-carbon transition. Such inertia is also argued to be region-dependent, increasing proportionally with a region's refining operations intensity. Hunt et al. [51] analyze alternative business models that can be implemented at the level of crude oil and gas industries. They suggest that due to infrastructure compatibilities, crude oil and gas refineries could smoothly shift towards a low-carbon economy. Finally, Gabrielli et al. [52] analyze how different Norwegian ports might adapt to the low-carbon transition in general, with a particular emphasis on increasing electrification. They suggest that industrial sector coupling and the integration of multiple energy carriers (e.g., biofuels, hydrogen, and renewable electricity) are key to achieving a flexible and efficient low-carbon port system. However, that study further stresses that such transitions must be assessed at the level of individual ports, since successful adoption depends on specific local characteristics such as nearby industries, geographic location, and ownership structures.

Although the insights from the aforementioned studies on how the energy ports and their confined crude oil and gas industries can shift their fossil-based portfolio towards a low-carbon economy, no comprehensive global energy systems modeling, combined with the participation of key stakeholders, has been conducted to assess the future of local energy port clusters.

1.3. Contribution to literature

Two research gaps are addressed in this study. First, there is a lack of a comprehensive analysis on the future role of liquid fuels in general and synthetic liquid fuels in specific, that (i) combines a cost-optimization modeling exercise with an interaction with different players of the energy system; but also (ii) treats the role of these fuels as context dependent, and thus, sensitive to different socio-economic trends. Secondly, no study was found to establish a continuous interaction between a cost-optimization model exercise with stakeholders' participation as a key tool to assess the global supply and demand for future liquid refinery products, while understanding the role of energy port clusters as key players of a low-carbon transition.

Hence, this study targets to assess the future role of liquid fuels by integrating cost-optimization model exercises and stakeholders' participation in a single analytical framework. The suggested interaction makes two major contributions to existing literature. First, it facilitates a novel understanding of the role that liquid fuels, specifically synthetic liquid fuels, might play in a low-carbon transition, both at a global level and according to a local energy port cluster perspective. By applying modeling scenarios, which narratives are grounded in different socio-economic trends but also local specifications, it explores alternative directions in which the world may evolve, each leading to distinct configurations of future energy systems. Secondly, this study contributes to the energy systems modeling community by explicitly reflecting on the role that continuous and collaborative discussions between energy systems modelers and local stakeholders may have as a good modeling practice.

1.4. Aim and structure of the paper

The main aim of this study is to assess the future of liquid fuels by addressing the following questions: (i) What role do liquid fuels play in a low-carbon transition, and how does this role vary according to a range of uncertainties as depicted by different socio-economic trends and varied modeling parameters?; (ii) How do local energy port clusters envision the future role of liquid fuels (represented by the case of the Port of Gothenburg) and how can local knowledge contribute to ESOMs?

Section 2 describes the method and its development, combining stakeholder interactions with a global cost-optimization model, as well as presents the local energy port cluster system used as the case study (Port of Gothenburg). Section 3 outlines the main outcomes from applying the developed method, focusing on how the role of liquid fuels varies according to different socio-economic narratives, but also global cost-optimization and local perspectives. Section 4 concludes with a discussion, highlighting the importance of considering both global and local perspectives when assessing the future role of liquid fuels, and identifying areas for future work.

2. Method

The present study investigates the role of liquid fuels in the global low-carbon energy transition under different socio-economic scenarios, focusing on transport and industrial feedstock-related energy demands. By selecting a specific local energy port cluster as a case study (see Section 2.1.4 for more details), this study expands its scope to understand how this local cluster envisions the future role of liquid fuels, while sharing their related low-carbon local initiatives and challenges.

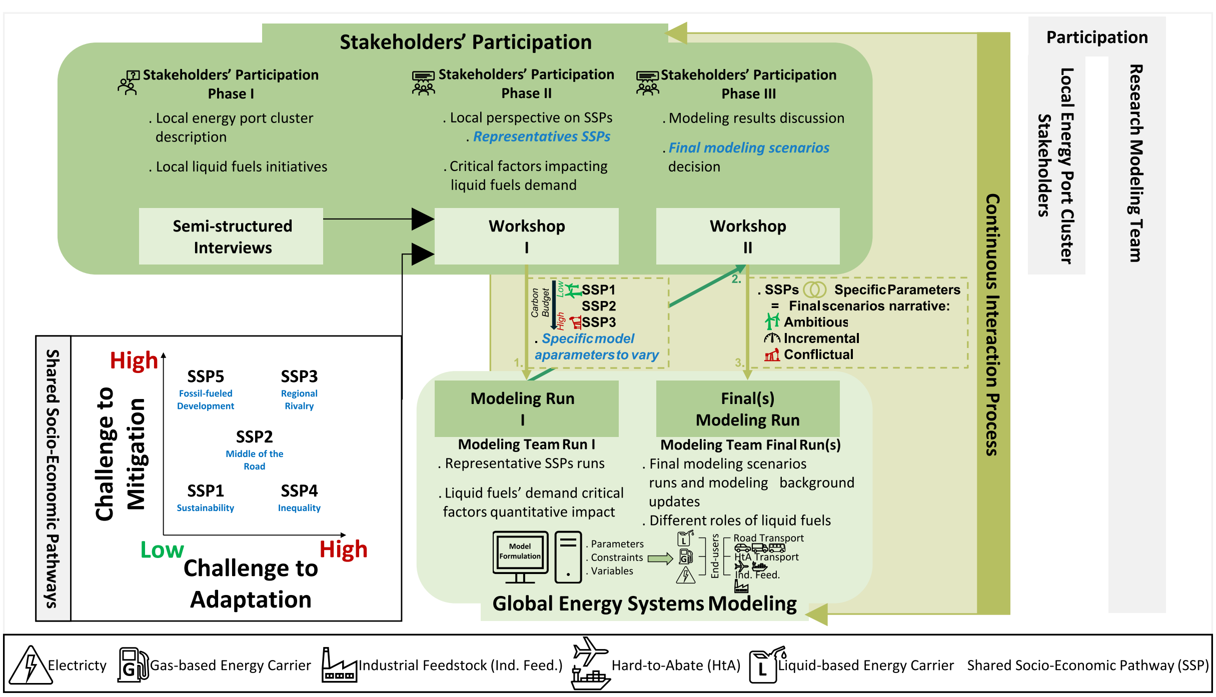

Fig. 1. - Single analytical framework outline formulated according to a continuous interaction between two perspectives: Stakeholders' Participation and Global Energy Systems Modeling. Stakeholders' participation was structured into three phases. Phase I refers to the initial contact between the research modeling team and stakeholders, facilitated through semi-structured interviews that mapped an overall understanding of the dynamics within the local energy port cluster, especially focusing on local liquid fuels initiatives. Phases II and III involved direct engagement between the research modeling team and participating local stakeholders through two workshops. During these two workshops, the modeling rationale (Phases II and III) as well as results (Phase III) were continuously discussed, leading to the identification of the Final Modeling Scenarios to be modeled and the definition of the narratives to be captured. These narratives combined different SSPs with critical factors identified as influencing the demand for liquid fuels, which were subsequently incorporated as specific model parameters to vary. Throughout Stakeholder's Participation Phases II and III, continuous modeling runs were conducted based on stakeholder input as well as background modeling updates (i.e., Modeling Run I and Final Modeling Run(s)). The resulting cost-optimized outcomes were actively shared and discussed with stakeholders, in addition to the three established phases of stakeholders' participation. G, Gas-based Energy Carriers; Ind. Feed., Industrial Feedstock, HtA, Hard-to-abate Energy Sectors; L, Liquid-based Energy Carriers; SSP, Shared Socio-Economic Pathways.

The local energy port cluster contributed to the modeling exercise by participating in the identification of *specific model parameters to vary* and the associated creation of the *Final Modeling Scenarios'* narratives.

The method applied in this study is defined as a single analytical framework that combines different phases of local energy port cluster stakeholders' participation with runs of a cost-optimization energy systems model. The single analytical framework, as presented in Fig. 1, includes two main perspectives: Stakeholders' Participation and Global Energy Systems Modeling. These two perspectives will be presented in the coming subsections.

2.1. Stakeholders' participation

Energy transitions, as suggested in literature (see e.g., [53]), might be assessed as context-specific, benefiting from a local energy cluster perspective. Such a perspective offers a comprehensive view of the local cluster structure and operation dynamics, highlighting how different components are interconnected [54–56]. As indicated in the referred literature, the local energy cluster understanding might result in better anticipation of how the system will respond to specific stimuli, allowing the identification of system enablers (i.e., components that facilitate the implementation of an action without compromising system performance) and barriers (i.e., components that increase the system's inertia towards transition). Accordingly, a local energy cluster perspective was added in this study through three different phases of stakeholders' participation i.e., Semi-structured Interviews, Workshop I, and Workshop II, as shown in Fig. 2. The stakeholders' participation was defined by the involvement, as well as collaborative and continuous participation of key stakeholders within the energy port cluster at different phases of this research.

Fig. 2 presents schematically the framework based on different phases of the stakeholders' participation. A more detailed description, including methodological procedures as well as key outcomes from the workshops and interviews, is provided in the Supplementary Material (Section S1.).

2.1.1. Phase I: semi-structured interviews

The semi-structure interview questions were developed by reviewing relevant legislation, academic literature, and the sustainability reports of the participating companies. The interview format (see Section S1.1.1. in Supplementary Material for more details, including interviews' guide) was designed to encourage participants to reflect freely while keeping facilitator input to a minimum. The interviews (40–90 min) were recorded, transcribed, and translated (i.e., all but one were conducted in Swedish). The transcripts were then analyzed thematically by systematically identifying, organizing, and interpreting patterns of meaning (i.e., themes, presented in Supplementary Material S1.2.2.).

The semi-structured interviews enabled in-depth discussions, providing descriptions and insights into the local energy port cluster's dynamics and how these dynamics might change in response to a low-

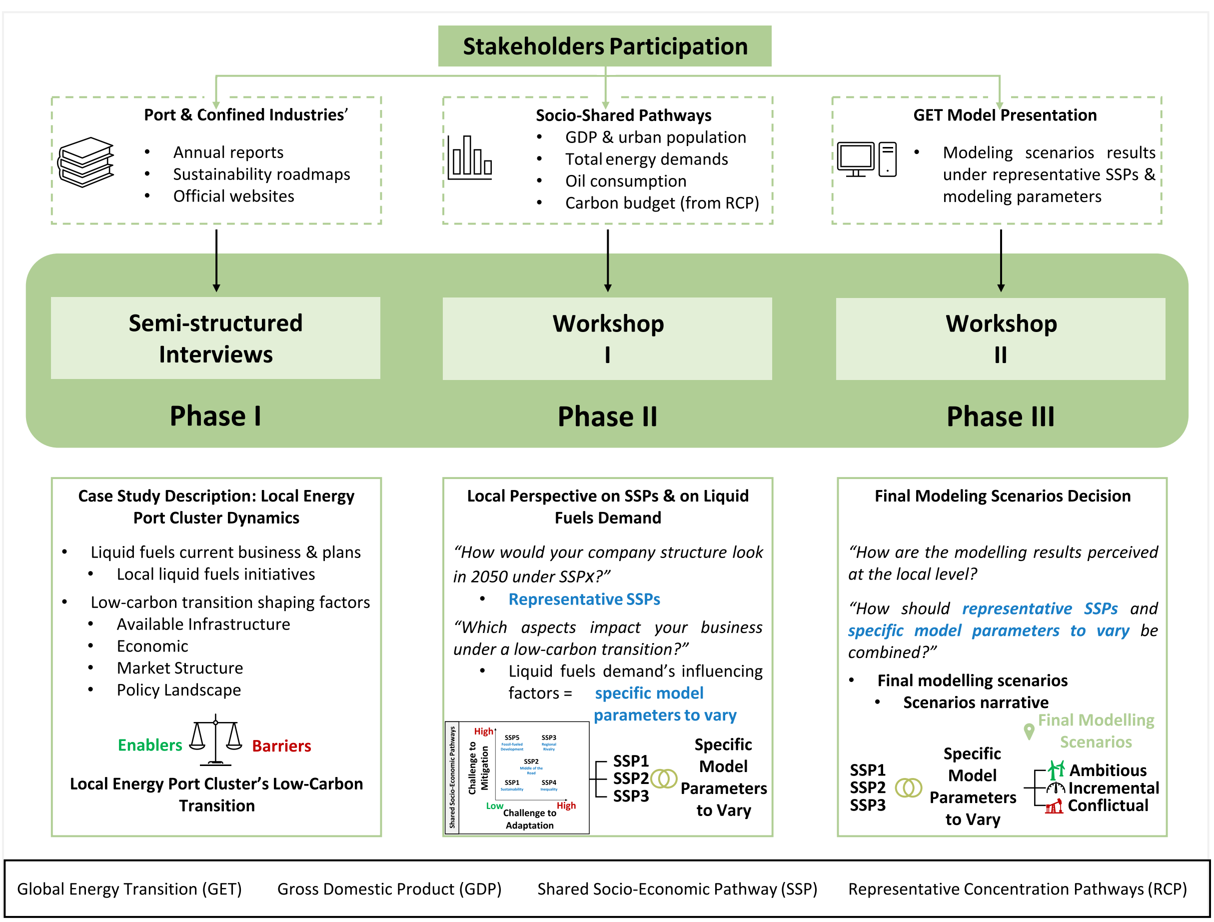

Fig. 2. - Stakeholders' participation outline based on three different stages of involvement. Phase I, through semi-structured interviews, accounts for stakeholders' involvement that serves as context knowledge and overall understanding of the dynamics within the local energy port cluster build-up. Phase II and Phase III present the workshops carried out in collaboration between the research modeling team and the local energy port cluster stakeholders. As the main outcome of the three stakeholders' participation phases, the final modeling scenarios and corresponding narratives (i.e., a mapping of which specific model parameters to vary in the model runs according to each narrative) were identified. GET, Global Energy Transition; RCP, Representative Concentration Pathways; SSP, Shared Socio-Economic Pathway.

carbon society. Considering the liquid, and mainly fossil, fuel-based dynamic of the local cluster, the semi-structured interviews focused on understanding how such could shift according to strict climate reduction goals. Through these collaborative discussions, particular attention was given to understanding how the role of liquid fuels may evolve in the future. In collaboration with the research modeling team, local energy port cluster stakeholders identified current and planned initiatives within the cluster aimed at supporting a continuous use of these energy carriers. Participants were further encouraged to share their views, identifying which initiatives might already or in the future support their stated and preferred trajectories. This included potential investment plans, pilot and demonstration projects, cross-industry collaborations, and necessary governance instruments.

During the semi-structured interviews, stakeholders were further encouraged to reflect on local factors that might impact the adoption of the local energy cluster structure to low-carbon budgets. The identified factors were perceived as either enablers or barriers to the local energy port cluster's low-carbon transition, also influencing the future role of liquid fuels. Notably, the influence of these factors (i.e., as either enablers or barriers) could shift depending on the different contexts, namely (i) economic (i.e., impact on the overall cost of a given company, including a projection of potential needed investments); (ii) infrastructure availability (i.e., readiness of the infrastructure in place for the different stages of the supply chain of liquid fuels); (iii) market (i.e., assessment of current and future liquid fuels demands including resource availability, as well as different consumer groups); as well as (iv) policy landscape in place (i.e., interlink between liquid fuel demand policy instruments – "command-and-control" or market-based as well as local energy port cluster climate commitments).

Overall, through semi-structured interviews, the modeling research team had the opportunity to enhance their knowledge of the local energy port cluster and its specific characteristics. This initial understanding was fundamental in shaping the design of the workshops in Phase II and Phase III. The part of the interview results that was presented in the two workshops is summarized in the Supplementary Material (S1.2. and S1.3.).

2.1.2. Phase II and III: Workshops

Following Phase I of the stakeholders' participation, the involved actors were invited to participate in two workshops – Workshop I and Workshop II –, representing Phase II and Phase III, respectively.

2.1.2.1. Workshop I. Workshop I focused on a presentation by the research team, who shared key insights from the semi-structured interviews. These findings provided a preliminary understanding of the low-carbon roadmaps developed by the stakeholders building up the local energy port cluster, as well as their perspective on the future role of liquid fuels. At this stage, the research modeling team has summed up the identified low-carbon factors, describing how those factors – available infrastructure, economic, market structure, and policy landscape – have been linked by the semi-structured interview participants as either being enablers or barriers of such transition.

During this workshop, stakeholders were also introduced to the narratives of the five existing SSPs. The narratives were extended to include how each of the five pathways depicted Gross Domestic Product (GDP), population, urbanization, total energy demands (including oil consumption), as well as carbon budgets, to evolve over the future. Using these narratives as a foundation, in groups, participants were invited to reflect on what each SSP would indicate for their local energy cluster and how liquid fuels demand potentially could evolve accordingly.

Collaboratively, the five SSPs were narrowed down to three SSPs, the *Representative SSPs*. The chosen SSPs depicted a well-covered range of plausible futures, ranging from a context defined by low climate mitigation and adaptation challenges (SSP1) to the opposite case, where regional rivalries result in high climate mitigation and adaptation challenges (SSP3). To better complement a potential comparison between these two extreme SSPs, a "*middle of the road*" (SSP2) was added, acting as a base case scenario, to the *Representative SSPs*.

Considering the focus of this research towards understanding how the role of liquid fuels might evolve in the future, the dialogue fostered in Workshop I, resulting in the identification of the *Representative SSPs*, also deepened the understanding about which potential "critical" parameters could be assessed in the model, and thus contributed to defining which *specific model parameters to vary*. The content and the individual steps of Workshop I are described in more detail in the Supplementary Material (Section S1.2.).

2.1.2.2. Workshop II. Between Workshop I and Workshop II, the modeling team carried out different modeling runs, based on the different combinations between the identified *Representative SSPs* and the identified *specific model parameters to vary*. These parameters include (i) carbon storage potential; (ii) biomass availability; (iii) interregional tradability; and (iv) the availability of new road vehicles having internal combustion engines (ICEs), and are clearly presented in Section 2.2.3 and Fig. 5.

Following the first round of model runs, Workshop II was held to present the modeling exercise conducted, along with the initial modeling results. Workshop II included a collaborative discussion focused on how modeling results could be interpreted locally, but also how the role of liquid fuels varied under the different assumptions.

This discussion helped to define the narratives *Final Modeling Scenarios* to consider in the cost-optimization assessment of this study. This included how the three *Representative SSPs* were complemented with the *specific model parameters to vary* identified in Workshop I. The content and the individual steps of Workshop II are described in more detail in the Supplementary Material (Section S1.3.).

In short, both Workshop I and Workshop II facilitated a contextual validation of the modeling rationale and related assumptions, with some local insights being considered in the *Final Modeling Scenarios*' narratives, by being transcribed into *specific model parameters to vary*. Stakeholders' insights from Phase I and Phase II have, in this sense, contributed to the selection of key scenario parameters, and preliminary model results, presented in Workshop II, were used to refine and confirm the modeling scenario narratives. Thereby establishing a two-way feedback process between stakeholders and the research modeling team. Although the semi-structured interviews, the Workshop I, and the Workshop II represented the main formal phases of stakeholders' participation, active collaboration was maintained throughout all phases of the research, serving as a continuous "reality check" to the cost-optimization modeling exercises. A detailed description of the cost-optimization model used in this research, as well as of the *Final Modeling Scenarios*, including the presentation of the *specific model parameters to vary*, are presented in Section 2.2).

2.1.3. Involved stakeholders profile

As illustrated in Table 1, 16 stakeholders participated in this study as part of the semi-structured interviews conducted, and/or as participants in Workshop I and Workshop II. This stakeholders' heterogeneity was essential to ensure a broad and holistic understanding of the key actors and factors influencing the energy port cluster's operation, investment decisions, and overall dynamics. While the 16 involved stakeholders provided inputs and local perspectives, the research design, analysis, and conclusions were developed independently by the research modeling team.

2.1.4. Case study overview: Port of Gothenburg

Located on the west coast of Sweden, the municipality-owned Port of Gothenburg is the largest and busiest port in Scandinavia [73]. Besides the company Port of Gothenburg, the port gathers other key activities

Table 1
- Overview of participating stakeholders within the local energy port cluster and their involvement across the participation phases of this research. The symbol "O" indicates active participation in a given phase, while "NP" indicates no participation. The letters "A," "B," and "C" identify cases where more than one company from the same type participated. CEO, Chief Executive Officer.

Type of Company ∈ Local Energy Port Cluster		Participation Stakeholders' Role in Company	Semi-structured Interviews	Workshop I [57]	Workshop II [58]
Bunker Supplier	A	CEO	O [59]	O	O
		Operational and Commercial Manager	O [60]	O	NP
	B	CEO	O [61]	O	NP
Fuel Producer	A	Business Development Team Representative	O [62]	O	O
		Sustainability Manager	NP	NP	O
	B	Business Development and Innovation Team Representative	O [63]	NP	NP
	C	Business Unit of Sustainability and Future Business Manager	O [64]	NP	NP
		Business Development and Innovation Team Representative	O [65]	O	O
Gas Infrastructure		Business Innovation Manager	O [66]	NP	O
Port		Operational Manager	O [67]	O	O
		Innovation and Port Development Representative	O [68]	O	O
		Port's Development Manager	O [69]	O	O
		Business Area Energy	O [70]	O	O
Storage Company	A	CEO	O [71]	O	O
	B	Business Innovation Team Representative	NP	O	O
	C	CEO	O [72]	NP	O

and actors influencing its dynamics, forming a local energy port cluster, with actors such as refineries, storage, energy, and shipping companies [74].

The energy-related operations at Port of Gothenburg are split into three terminals, handling a wide range of both liquid bulk and refined products, such as crude oil, gasoline, diesel, and biofuels. As part of its ambitions in mitigating global warming, the Port of Gothenburg has committed to achieving net-zero GHG emissions before 2045 [75]. This goal has alerted the various stakeholders to an impending shift in the dynamics of the local energy port cluster. Such a shift underscores the need to understand future energy demand in terms of the types and volumes of energy carriers to be produced, stored, and traded.

In this context, the Port of Gothenburg expresses the need to explore the future potential of liquid fuels as a strategic guide for upcoming investments. Accordingly, the local energy port cluster, including the Port of Gothenburg, was selected to be a good case study for this research.

2.2. Global energy systems modeling

A cost-optimization model – Global Energy Transition (GET) version 11 [76] – was applied to this study. The GET model, which uses the General Algebraic Modeling System (GAMS) framework, was first developed by Azar et al. [77] and, since then, has been continuously updated by different researchers at Chalmers University of Technology (see e.g., [78–82]). As a long-term optimization model, and contrarily to simulation models (i.e., predictive tools generating results based on historic data [see, e.g., [83]]), GET is not applied to predict future outcomes or forecast the development of energy systems. Rather, as an optimization tool, GET focuses on the understanding of system behavior, interactions, and the relationships among energy technology options across various sectors. As a bottom-up linear optimization model, GET is characterized as a technology-explicit mathematical tool, thoroughly representing the techno-economic dynamics of global energy systems. Despite the detailed representation of energy systems, GET is regarded as a partial-equilibrium model, meaning it is limited to techno-economic interactions between energy carriers and energy-use technologies.

The GET model's objective is to find the lowest cost solution that satisfies the different energy demands, under different modeling constraints and assumptions, over the entire modeled time horizon. The total system cost, as the objective function, is minimized as shown in Eq. 1:

$$Total\ System\ Cost = \sum_{region,t} \frac{t_{step} * Annual\ Cost_{(region,t)}}{(1+r)^{t_{step}*(ORD(t)-1)}} \quad (1)$$

In the case of the present study, $Annual\ Cost_{(region,t)}$ sums together different costs, such as primary energy costs, technology and infrastructure investment costs, fixed and variable operation and maintenance (O&M) costs, carbon storage cost, and energy carriers transport cost. Over all modeled regions (*region*) and whole time horizon (t), the sum of annual costs at each timestep is multiplied by the number of years in between each timestep ($t_{step} = 10$) and discounted relative to the reference year (2010). The modeled time horizon range between 2010 and 2150, in a decade interval, where $ORD(t)$ is a GAMS operator that returns the position of an element within a set as an integer (e.g., ORD (2010) = 1 and ORD(2150) = 15). This study used a social discount rate (r) of 5% [82], applied to all technologies and modeling regions. Worth mentioning is that the modeling exercise, conducted with GET, divides the world into 10 different modeling regions (*region*) (see Fig. 3), and related results will be presented with a temporal resolution spanning over six decades, from 2020 to 2070.

As represented in Fig. 3, GET model operates according to a load balance constraint, where different end-users' energy demands, as a parameter exogenously defined, are required to be met at every time step, through the conversion and interregional trade of some energy carriers (both primary energy sources and final energy carriers). Such a mechanism operates under the assumption of perfect foresight, meaning the model has full knowledge of the exact demands, constraints, and costs over the entire modeled time horizon. In the context of this study, for each of the regions considered, eight primary energy sources are considered: (i) crude oil; (ii) coal; (iii) natural gas; (iv) uranium; (v) biomass; (vi) hydro; (vii) wind; and (viii) solar. Additionally, four overarching end-user demands are represented: (i) electricity sector; (ii) heat sector; (iii) industrial feedstock; and (iv) transport. GET 11 further considers flexibility options captured by two types of storage: energy storage of both electricity and hydrogen; and carbon storage.

2.2.1. Liquid fuels representation

In this study, liquid fuels can be derived from the fractionation of crude oil, but also synthetic liquid fuels originating from different chemical syntheses are considered.

Within synthetic liquid fuels, a total of six production pathways (three fossil-based and three non-fossil-based) are considered according to the carbon source, see Fig. 4. Fossil-based synthetic liquid fuels are presented in this study through coal and gas-to-liquid processes based on Fischer-Tropsch synthesis (i.e., a process that converts carbon monoxide and hydrogen into liquid fuels, see e.g., [84]). Contrarily, synthetic liquid fuels, following, e.g., Kanchiralla et al. [6], include both biofuels and electrofuels. According to the six production pathways assumed for synthetic liquid fuels, the carbon atoms can be captured from (i) flue

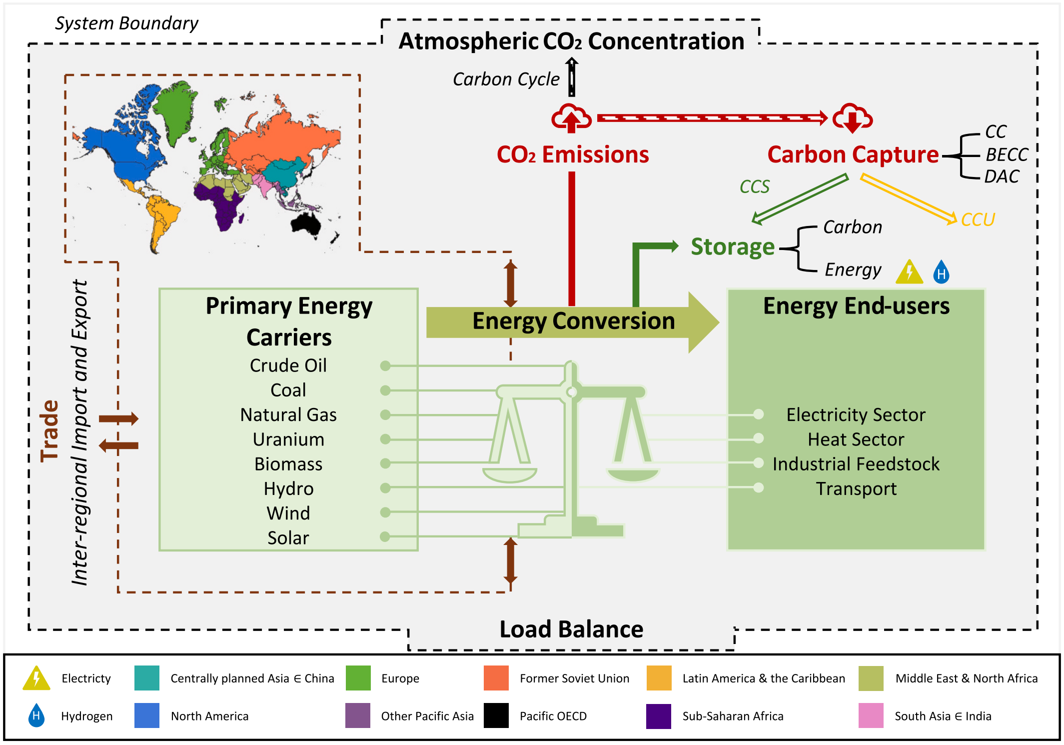

Fig. 3. GET 11 modeling framework applied in this study. Three carbon capture technologies are considered, including both fossil and biogenic-based carbon, (i) Carbon Captured from Flue Gases from the Combustion of Fossil Fuels (CC); (ii) Bioenergy with Carbon Capture (BECC); or (iii) Direct Air Capture (DAC). Any of these three technologies can be used as either carbon capture utilization (CCU) or carbon capture storage (CCS). Maps were generated for the specific purpose of this study, using the Quantum Geographic Information System (QGIS) 3.36.2 [86].

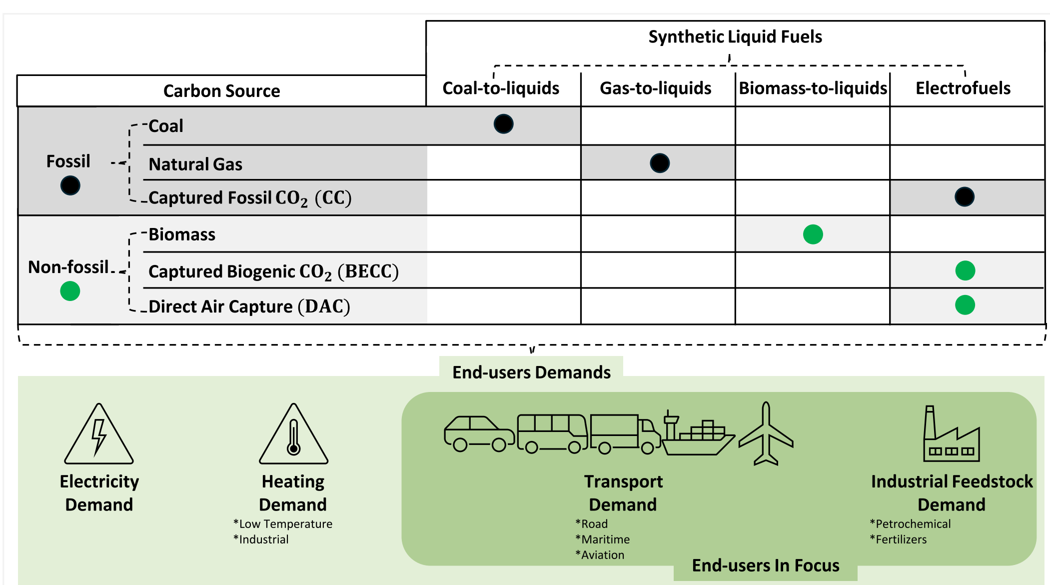

Fig. 4. Matrix of the synthetic liquid fuels (i.e., liquid fuels produced through chemical synthesis rather than crude oil refining) considered in this study. Based on carbon origin, these energy carriers can be either fossil-based (dark grey) or non-fossil-based (light grey). Although the GET model covers different energy sectors (i.e., electricity, heating, transport, and industrial feedstock), transport and industrial feedstock are the considered end-users in focus in this study. BECC, Bioenergy with Carbon Capture; CC, Carbon Captured; DAC, Direct Air Capture.

gases from the combustion of fossil fuels (CC); (ii) bioenergy with carbon capture (BECC); or (iii) using direct air capture (DAC). Methanol (MeOH) is considered to be the cheapest large-scale liquid synthetic energy carrier [85] and, thus, considering the cost-optimization nature of the GET model, used as a proxy and a good representative of the synthetic fuels.

Not only are liquid fuels considered in the modeling exercise. Other energy carriers, such as ammonia (NH_3), crude oil-based fuels, electricity, hydrogen (both liquified (LH_2) and compressed (CH_2)), and liquified methane (LCH_4), are also considered in the model.

2.2.2. End-users in focus

As previously introduced, the rationale of the GET model operates according to a load balance dynamic, defined as an equilibrium established between supply and demand at every modeled time step. As a variable, supply is an outcome of the cost-optimized exercise conducted by the GET model, while demand is set as an exogenous modeling parameter.

Accordingly, the annual demands for the different assumed end-users (i.e., electricity sector, heat sector, industrial feedstock, and transport sector, as presented in Fig. 4) are included in the modeling. These demands vary according to the three modeled scenarios, mainly due to differences in projections of GDP and population growth [87–89]. In this study, the transport sector and industrial feedstock were assumed as the end-users in focus.

The transport demand is split into three main segments, namely road, shipping, and aviation. Rail is included but not the focus of this study due to the already in place electrification advancements. Overall, the road transport demand assumed in this study follows the transport considerations previously published by Lehtveer et al. [15]. Similarly, the shipping transport demand follows the same guidelines as presented by Kanchiralla et al. [76], accounting thus for a thorough representation of different ship categories, according to which different operation dynamics and energy demand are defined. Additionally, as presented by Kanchiralla et al. [76], the aviation module has been further improved in the model version presented in this study by separating aircraft into short-, medium-, and long-range categories. This distinction improves the analysis by recognizing that technological solutions in aviation are highly sensitive to flight distances. The split is supported by a comprehensive update of techno-economic parameters, which are tailored to the specific operational characteristics of each range category.

At the industrial feedstock level, this study follows the same assumptions as presented by Grubler et al. [90], representing, thus, both agricultural and petrochemical sectors. Accordingly, the feedstock sums together the non-energy use of primary energy sources, e.g., for the production of agricultural fertilizers and plastics.

Despite the scenario-specific variations in the total energy demand of the different end-users, the total energy demand and associated carbon emissions were calibrated up to and including the year 2022, using BP Statistical Review of World Energy [91].

Detailed techno-economic data and related assumptions of end-use demand are presented in the Supplementary Material (see Section S2.2.).

2.2.3. Modeling scenarios: A continuous interaction between stakeholders' participation and global energy systems modeling

The role that liquid fuels might play, in future defossilized global energy systems, will be greatly influenced by the different end-users' demands. The referring demands are further shaped by how different socio-economic factors might unfold. Such socio-economic factors are assessed by this study through the SSPs framework [34].

As a base for the different socio-economic trends assumed in this study, three *Representative SSPs* were chosen collaboratively by the local port cluster stakeholders and the research modeling team, as covering a mitigation and adaptation challenges gap ranging from low (SSP1) to high (SSP3). By adding the "*middle of the road*" SSP2 a broad range of possible future global energy systems was depicted.

From the SSPs, this study directly retrieved future projections on socio-economic factors (i.e., GDP, total as well as urban population, and non-transport end-user energy demands). This study also adopted the same carbon budget reflected in the SSPs and as proposed by the Representative Concentration Pathways (RCPs).

Moreover, as a result of the stakeholders' participation three-phase process, the identified critical parameters towards future liquid fuel demand were integrated in the modeling exercise as *specific model parameters to vary*. These parameters were adjusted in the GET model to be more in line with the SSP narratives (see Fig. 5). While the selection of modeling parameters was determined collaboratively by stakeholders and the research team, assigning quantitative indicators to these parameters remained the responsibility of the research team. Based on a state-of-the-art review, the team deliberately determined which quantitative values, consistent with the narratives of each modeling scenario, should be used to vary the identified parameters. The adjusted assumptions and corresponding quantitative indicators were also verified by the stakeholders' participation during Workshop II (see Section 2.1.2). Accordingly, as shown in Fig. 5, three modeling scenarios – *Ambitious*, *Incremental*, and *Conflictual* – were assessed in this study.

The *Ambitious Scenario*, as an extension of SSP1, represents a widespread sustainability future due to a high societal environmental awareness. Such a scenario is illustrated by a relatively low cumulative carbon budget of 700 $GtCO_2$ between 2010 and 2100. The *Incremental Scenario*, by following the same trend as SSP2, transcribes historic and current energy trends into the future. Under this scenario, the future does not necessarily reflect strong efforts to address environmental challenges, but it also does not significantly worsen them, assuming a cumulative carbon budget of 905 $GtCO_2$. The *Conflictual Scenario*, as reflecting SSP3, is shaped by geopolitical tension, calling for a great focus on energy independence, seen as key to balancing the potential threat to energy national security. As a result, under this scenario, environmental concerns take a back seat, leading to increased exploitation of existing domestic resources, typically fossil-based, but also biomass. Consequently, the cumulative carbon budget is assumed to be 1255 $GtCO_2$.

2.2.3.1. Carbon storage potential.

CCS may be a key carbon abatement technology (see e.g., [92]). Such technology is often linked to industrial sites, capturing the carbon atom from CO_2 industrial sources and transporting it to underground facilities for permanent storage (i.e., deep aquifers or depleted oil and gas fields) [93].

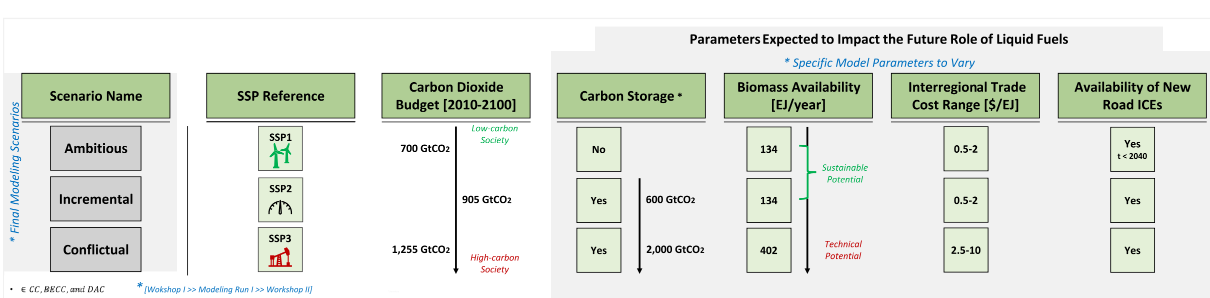

Fig. 5. Final modeling scenarios matrix, highlighting the main constraints and parameters assumed in this energy systems modeling exercise. The final modeling scenarios and identification of specific model parameters to vary are an outcome from a continuous interaction between different phases of stakeholders' participation and modeling runs, as presented in Section 2.1. BECC, Bioenergy with Carbon Capture; CC, Carbon Captured from Flue Gases from the Combustion of Fossil Fuels; CO_2, Carbon Dioxide; DAC, Direct Air Capture; ICEs, Internal Combustion Engines; SSP, Shared Socioeconomic Pathways.

The storage potential associated with CCS remains uncertain, becoming a limiting factor on the feasibility of such a technology (see e.g., [94–97]). According to the existing literature, such potential varies according to different concerns on CCS technical maturity, cost, public acceptance, environmental risks, fossil fuel lock-ins, and potential leakage. Hence it is important to assess the potential competition between carbon sequestration and carbon utilization, that is, the trade-off between a prolonged reliance on crude oil-based energy carriers and a shift towards a higher share of synthetic liquid fuels, particularly electrofuels.

Reflecting on these trade-offs, the *Ambitious Scenario* assumes a carbon storage potential of 0 $GtCO_2$, due to high environmental concern and assumed lack of public support for CCS. In the *Incremental Scenario,* the carbon storage potential is assumed to be 600 $GtCO_2$, representing the lower bound of estimated storage in geological formations [98]. The *Conflictual Scenario* assumes a carbon storage of 2000 $GtCO_2$, reflecting an interest in using locally extracted fossil fuels [98].

In this GET version, there are three carbon capture technologies, considering both fossil and biogenic-based carbon and thus, including flue gases from the combustion of (i) fossil fuels (CC); (ii) biomass (BECC); or (iii) captured directly from the air (DAC). Any of these three technologies can be used as either CCU or CCS. This is the case for all modeling scenarios, except for the *Ambitious Scenario*, where the carbon storage potential, as presented in Fig. 5, is set as zero. In the *Incremental* and *Conflictual Scenarios*, the choice between CCU and CCS is determined by the cost-optimal modeling rationale.

2.2.3.2. Bioenergy availability. Biomass and derived bio-products are argued in the literature as key in shaping a low-carbon society (see e.g., [99]). For some, biomass is identified as a system integrator, due to its wide applicability among different energy sectors (see e.g., [32]). Yet, the mentioned literature also discusses biomass as being a limited resource, and thus, its availability becomes a decisive factor in shaping a global energy transition.

Accordingly, this study assumed different biomass availability as a tool for analyzing cross-sectoral interaction. Such an analysis further highlights the willingness to pay for biomass when assumed as a scarce resource.

Biomass availability ranges according to different categories, i.e., theoretical, technical, economic, and sustainable [100]. For both *Ambitious* and *Incremental Scenarios*, biomass availability is considered according to a sustainable perspective, represented by a global potential of 134 EJ/year [15]. Compared to the other two scenarios, in the *Conflictual Scenario*, the global biomass potential triples to 402 EJ/year, representing a technical potential, value in line with the assumptions presented by Hoogwijk et al. [101].

2.2.3.3. Interregional trade. Interregional trade is identified as a key flexibility measure of energy systems, contributing to regions consistently matching their supply and demand (e.g., [102]). Yet, due to energy security concerns, such trade might be at risk due to national energy independence goals.

The cost of interregional trade is calculated based on the fuel property (i.e., boiling temperature, energy density, and storage requirement), investment cost, and distance between the trading regions (see Section S2.2. in Supplementary Material). For both *Ambitious* and *Incremental Scenarios*, depending on the energy carrier, interregional trade costs average at 0.5 USD/GJ, adding a component based on transport distances between the different regions and the energy density of the energy carrier. In the *Conflictual Scenario*, there is a focus on energy self-sufficiency, and thus, a relatively low interregional trade is expected. In reality, trade can be affected by different mechanisms, e.g., tariffs, import quotas, subsidies, and embargoes (see e.g., [103]), which is transcribed in this study by increasing the import cost by a factor of five, compared to the two other scenarios.

2.2.3.4. Availability of new road internal combustion engines. Despite the great technological advancements that advocate electricity as a key solution for lowering the carbon footprint of road transport, this segment still represents a high share of the total transport-related global emissions (see e.g., [104]). Such a trend follows the still current high ICEs' share in stock and sales of new road vehicles. To balance such a trend with a rapid intake of electric powertrains, different policymakers have been actively discussing the possibility of banning the sales of new ICEs post-2035 (see e.g., [105]). Accordingly, and in line with the socio-economic narrative of SSP1, ICEs' new sales are forbidden in the *Ambitious Scenario*, post-2040.

2.2.4. Sensitivity analysis

To investigate the uncertainty of selected parameters and the sensitivity of the modeling results to these parameters, a Monte Carlo analysis was performed.

The parameters to vary in the Monte Carlo analysis included the *specific model parameters to vary* in the scenarios of this study. However, to broaden the scope it did also include a few other factors discussed with the stakeholders, although less-emphasized compared to the *specific model parameters to vary* as well as parameters suggested in the state of the art as potentially influencing the supply and demand of liquid fuels.

Accordingly, the Monte Carlo analysis tested the sensitivity of parameters related to (i) global carbon storage capacity and cost; (ii) direct air capture cost; (iii) bioenergy availability; (iv) variables renewable energy sources (VRESs) investment cost; (v) stack battery, electrolyzers; and fuel cell techno-economic data; (vi) synthetic liquid and other alternative fuels production techno-economic data; as well as (vii) refueling and charging infrastructure investment cost.

To better assess the sensitivity of the tested parameters – and to capture both different maturity levels of a given technology and different world contexts that might accelerate or hinder its development – each parameter value was varied uniformly between 0.5 and 1.5 times its base value. This approach follows that of Lehtveer et al. [15]. The Monte Carlo analysis was carried out with 500 model runs for each of the three modeling scenarios. The values of parameters randomly varied in the Monte Carlo analysis, are presented in the Supplementary Material (see Section S2.3.).

3. Results

This section presents the results from both the global cost-optimization model and on how stakeholders within the local energy port cluster envision the future role of liquid fuels towards a low-carbon energy transition.

3.1. Global and cost-effective insights into a low-carbon transition and future role of liquid fuels

According to the cost-optimization modeling, the results, influenced by the assessed *specific model parameters to vary*, differed between the three scenarios. In this section, only the results focusing on the scope of this study are presented.

3.1.1. Primary energy mix

Currently, as illustrated in Fig. 6, around 70% of the global primary energy mix comprises fossil fuel-based energy carriers (i.e., crude oil, coal, and natural gas). Within these fossil fuel-based energy carriers, crude oil contributes the highest energy share of nearly 50%. It is shown to be cost-effective to gradually phase out fossil-based energy carriers in all three scenarios, increasing renewable energy sources (RES), such as biomass, wind, and solar power.

Despite the common trends found over the three scenarios, the renewable share increases proportionally to a stricter carbon budget. Due to the stringent carbon budget constraints, the *Ambitious Scenario*

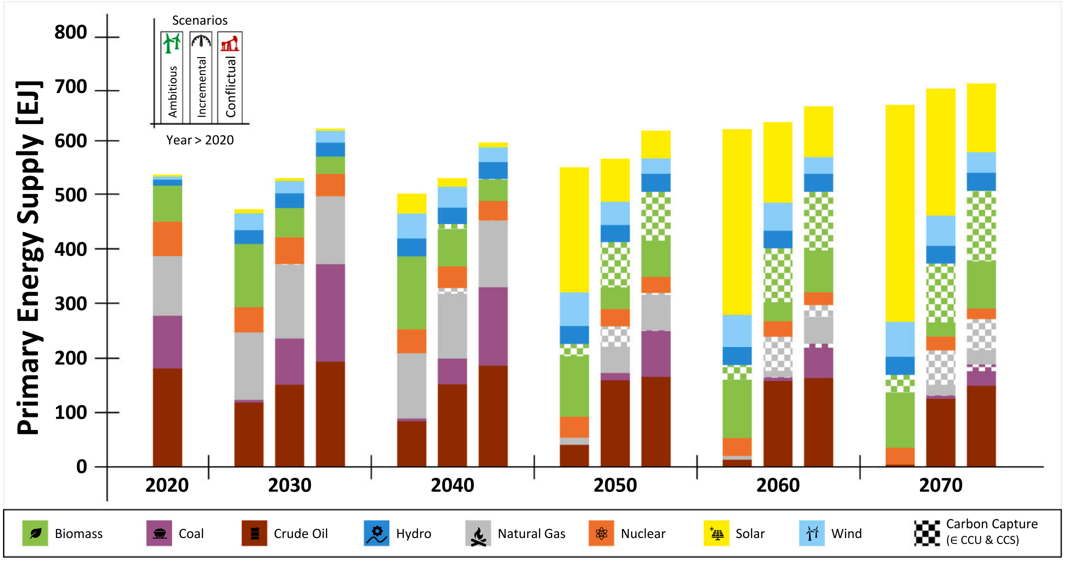

Fig. 6. Primary energy mix supplied summed over the 10 GET regions. The year 2020 is calibrated for all three scenarios, based on the BP Statistical Review of World Energy [91], being constant throughout the three scenarios. For years 2030–2070, the three bars present the result for the three scenarios, from left to right representing the Ambitious, Incremental, and Conflictual scenarios, respectively. Carbon Capture technologies are represented by a bi-colored square pattern and include Bioenergy with Carbon Capture (BECC), Carbon Captured from Flue Gases from the Combustion of Fossil Fuels (CC), and Direct Air Capture (DAC). Carbon Capture technologies can be used as both CCU and CCS.

sees renewables supplying over 50% of the energy mix from 2040 onwards. Among the available RES, solar power emerges the most, primarily because of its relatively low capital costs compared to both wind and biomass. As a result, solar becomes the dominant energy source after 2050. The transition to a renewable-based energy system brings ancillary benefits, such as overall energy efficiency gains. RES are generally more energy-efficient than fossil fuel-based carriers, resulting in reduced energy losses throughout the system. Consequently, a renewable-dominated system requires a lower total primary energy supply to meet the same demand. Relaxing the carbon budget, as in the *Incremental* and *Conflictual Scenarios,* delays the large-scale adoption of renewables to later years, compared to the *Ambitious Scenario*. As a cost-effective solution for meeting the relaxed CO_2 reduction targets, the model instead finds carbon storage more attractive. Examining the use of carbon storage technologies across the different scenarios highlights the relationship between carbon budget constraints and storage strategies. In the *Ambitious Scenario*, where the carbon budget is most stringent, carbon capture is found to be cost-effective when associated with biomass to be used as a feedstock for producing electrofuels. In contrast, the more relaxed carbon budgets of the *Incremental* and *Conflictual Scenarios* delay the energy transition and result in continued reliance on fossil fuels.

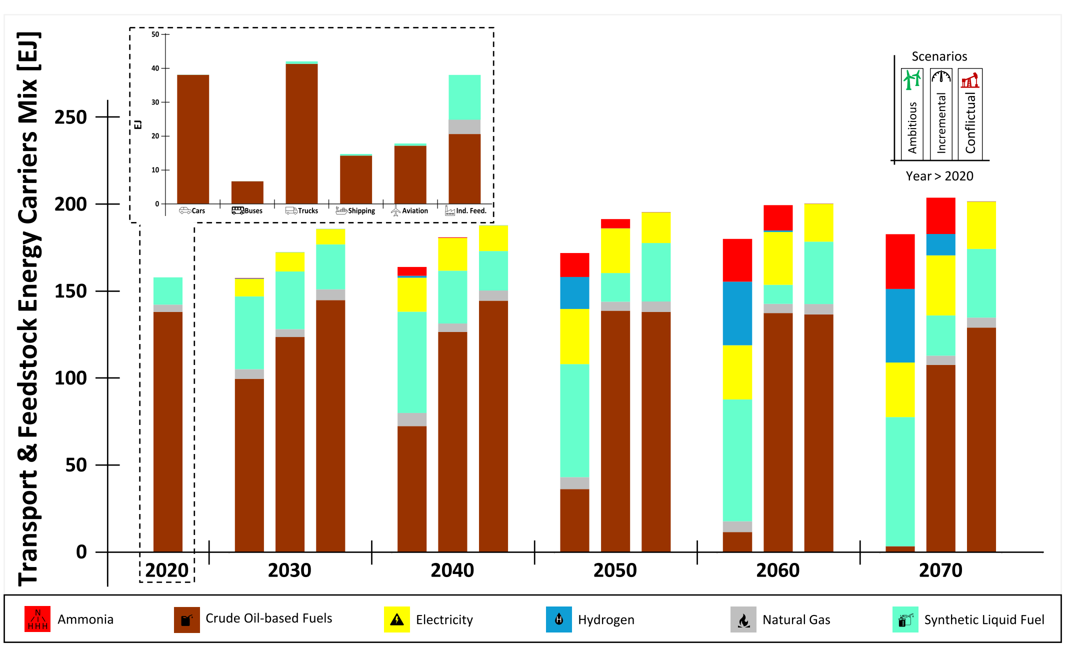

Fig. 7. Cost-effective energy carriers mix for the transport and industrial feedstock sectors, summed over the 10 GET regions. The year 2020 is calibrated as the same for all three scenarios, based on the BP Statistical Review of World Energy [91]. For years 2030–2070, the three bars present the result for the three scenarios representing, from left to right, the Ambitious, Incremental, and Conflictual scenarios, respectively. Ind. Feed, Industrial Feedstock.

3.1.2. Transport sector and industrial feedstock

Fig. 7 shows model results of the transport sector and industrial feedstock for the three scenarios. In 2020, both sectors were predominantly reliant on fossil fuels, mainly crude oil-based fuels, and in the case of industrial feedstock, a significant contribution from natural gas and synthetic liquid fuels.

Across all scenarios, model results show that liquid fuels persist but shift from crude oil-based to synthetic alternatives, depending on the stringency of the carbon budget. In the *Ambitious Scenario*, where carbon constraints are strictest, the model suggests that crude oil-based fuels are progressively phased out and replaced by synthetic liquid fuels, which become the dominant fuel type by 2050.

In both the *Incremental* and *Conflictual Scenarios*, crude oil-based fuels remain the dominant cost-effective energy carrier throughout the entire modeling period. However, the share of synthetic liquid fuels, along with other alternative fuels, varies over time between the two scenarios. The *Incremental Scenario* shows the lowest uptake of synthetic liquid fuels. This trend is largely explained by the cost-effectiveness and immediate availability of alternatives such as electricity and ammonia. Conversely, the *Conflictual Scenario* envisions greater use of synthetic fuels (compared to the *Incremental Scenario*), as it assumes full deployment of diverse production pathways, including fossil-based routes (e.g., coal and natural gas). This is enabled by a less stringent carbon budget, high carbon storage capacity, and biomass availability, as well as limited interregional trade, which favors the use of regionally available resources. Together, these factors enhance the long-term viability and attractiveness of synthetic liquid fuels in the *Conflictual Scenario*.

3.1.3. Road transport

Despite the current, as of 2020, crude oil-based fuels dependency experienced in road transport, as presented in Fig. 7, the cost-optimization modeling exercise's outcome reveals that the three considered road segments (i.e., cars, buses, and trucks) will experience different future trends.

Fig. 8 depicts how the model reacts to different assumptions, where the carbon budget and a ban on the sales of new road ICEs play key roles in shaping the trend.

Under more strict carbon budget, and assuming a ban on the sales of new ICEs post 2040, as in the *Ambitious Scenario*, road transport gradually shifts their oil-based fleet towards an increasing electrification, both direct (i.e., electricity used in electric vehicles (EVs), including both plug-in hybrids (PHEVs) and battery (BEVs)) as well as indirect (i.e., hydrogen applied in fuel cell electric vehicles (FCEVs)). While the model suggests rapid electrification advancement in the passenger car segment, liquid fuels, such as synthetic liquid fuels, continue to play a significant role in the short to medium term for heavy-duty road transport (i.e., trucks). The trucks sector's dynamics are shaped by the need for long driving ranges and the ability to carry large cargo volumes, which, due to the weight associated with the battery system, adds inertia to the transition towards electrified technologies. As a result, electrification in this segment is less a market-driven shift and more the outcome of policy mandates and regulatory incentives, such as a ban on the sales of new ICEs.

In the *Incremental Scenario*, as in the *Ambitious Scenario*, the model finds electrification a cost-effective solution for cars. This trend is supported by declining capital costs, as well as the increasing share of RES in the power sector (see Fig. 6), which is characterized by low marginal electricity costs. Nonetheless, other road transport segments, such as buses and trucks, experience a slower transition to low-carbon alternatives due to their specific operational demands, e.g., long driving ranges and high cargo capacity. As a result, they continue to show a high reliance on crude oil-based fuels throughout the modeling period. Synthetic liquid fuels are suggested as a transitional solution from the short- to long-term, maintaining a relatively constant share over time. This trend suggests that their adoption is connected to the need to comply with policy regulations, such as carbon budget constraints.

In the *Conflictual Scenario*, all road transport segments remain dependent on liquid fuels. While this dependence is balanced between crude oil-based and synthetic fuels in the bus and truck sectors, electrification is found to be an integral part of the passenger car energy mix in the long term. That is, also under a looser carbon budget, electrification of cars is a cost-effective solution.

3.1.4. Hard-to-abate sectors

The cost-effective fuel mix for shipping, aviation, and industrial feedstock is illustrated in Fig. 9. Overall, the hard-to-abate dynamics of the sectors considered result in a steady dependency on liquid fuels, ranging from crude oil-based to synthetic pathways, depending on different carbon budgets.

The *Ambitious Scenario* shows a rapid transition towards the use of synthetic liquid fuels, a shift that is particularly pronounced in the aviation and industrial sectors due to the lack of mature and cost-effective alternative technologies. Stricter carbon budgets further favor the adoption of ammonia, especially in the shipping industry.

In the *Incremental* and *Conflictual Scenarios*, loosening the carbon budgets makes it possible to prolong the use of crude oil-based energy carriers. Synthetic liquid fuels play a significant role in the *Conflictual Scenario* due to a less stringent carbon budget, ample carbon storage capacity, high biomass availability, and limited interregional trade. Under this context, synthetic liquid fuels benefit from the indirect use of fossil fuel energy carriers.

3.1.5. Liquid fuels production pathways

Beyond examining the role of liquid fuels in a low-carbon transition, this study also analyzes the kind of production pathways that are employed for these energy carriers (i.e., fossil-fuel, biomass, hydrogen-

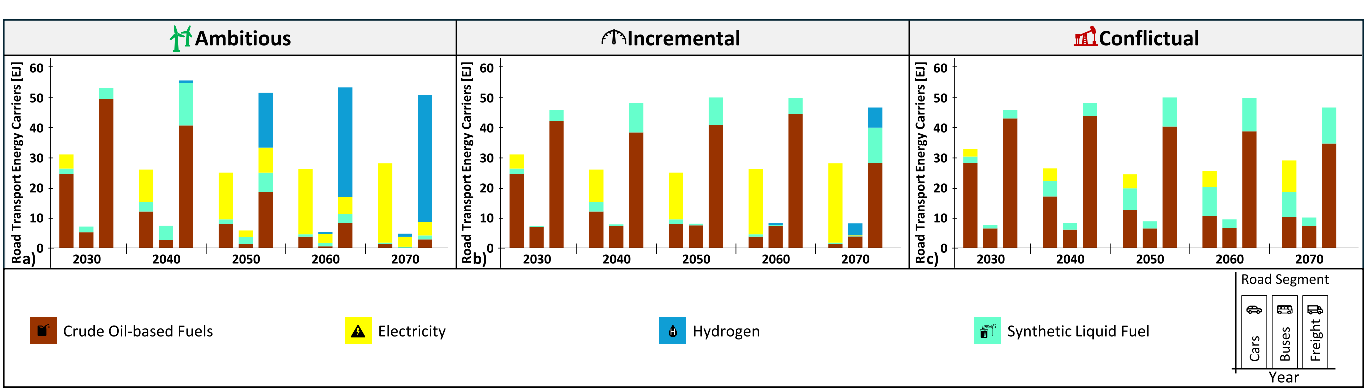

Fig. 8. Cost-effective energy carriers mix for road transport, summed over the 10 GET regions, presented for the three modeling scenarios (graphs a-c). For each year between 2030 and 2070, each bar represents a specific road segment, from left to right, representing Cars, Buses, and Trucks, respectively.

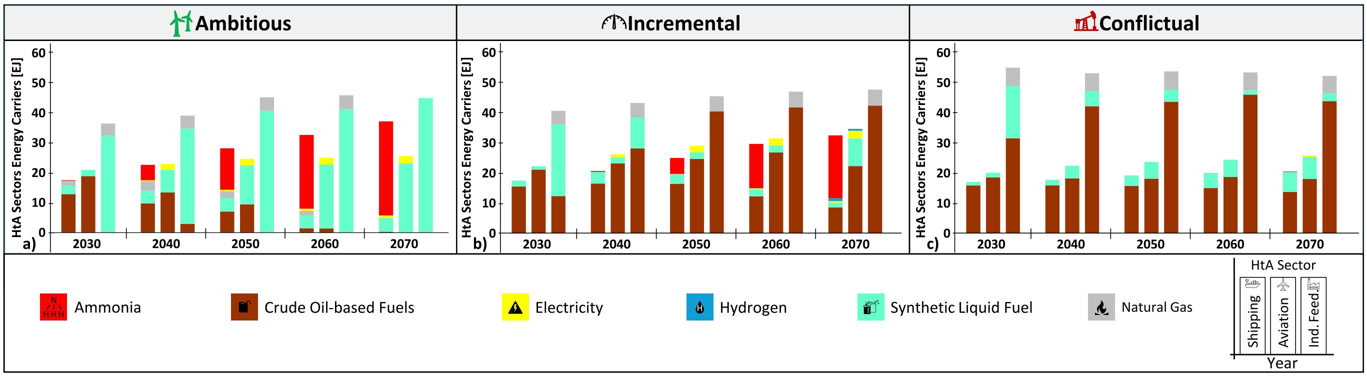

Fig. 9. Cost-effective fuel mix for the Hard-to-abate (HtA) sectors, summed over the 10 GET regions, presented for the three modeling scenarios (graphs a-c). For each year between 2030 and 2070, each bar represents a specific sector, from left to right representing Shipping, Aviation, and Industrial Feedstock, respectively. Ind. Feed, Industrial Feedstock.

based). Accordingly, and as presented in Fig. 10, synthetic liquid fuels are characterized by production pathways that vary depending on the parameters assessed.

As previously discussed, synthetic liquid fuels achieve a higher share under stricter carbon budgets, i.e., in the *Ambitious Scenario*. Their compatibility with existing combustion technologies, but also existing fuel production and distribution infrastructures, makes them an attractive option, supporting their continued use within the energy system. In the *Ambitious Scenario*, the production pathways for synthetic fuels shift over time from fossil fuel-based sources (e.g., carbon derived from natural gas) to biomass-based and eventually hydrogen-based (i.e., electrofuels) options. Biomass-based fuels play a more prominent role in the short to medium term, while hydrogen-based pathways become increasingly viable in the long term, benefiting from a power sector dominated by renewables and characterized by low marginal electricity costs as well as electrolyzers' technology maturity, defined by a decreasing capital cost.

Also under a loose carbon budget, high shares of synthetic liquid fuels are observed, i.e., in the *Conflictual Scenario*. This trend is driven by the combination of high carbon storage potential, biomass availability, and stricter interregional tradability assumptions. Overall, synthetic liquid fuels benefit from their production flexibility, as their carbon demand can be met by a variety of sources. Under less stringent carbon constraints, producing synthetic fuels from fossil-based sources (e.g., coal and natural gas) proves to be cost-effective, as it enables continued use of mature, market-established combustion technologies and existing infrastructure while still achieving moderate emissions reductions. In this scenario, higher biomass availability combined with increasing trade costs for energy carriers enhances the cost-effectiveness of domestic self-sufficiency, and thus, the use of domestically available energy carriers, as biomass and coal.

3.1.6. Monte carlo analysis

Fig. 11 presents the results from the Monte Carlo analysis on liquid fuels use in 2070, for the transport and industrial feedstock sectors, as a function of global carbon storage capacity (graphs a–c) and annual biomass availability (graphs d–f). These were the only two parameters identified as binding, with correlations R^2 above 0.1. Results for all the other tested parameters considered in the Monte Carlo analysis are provided in the Supplementary Material (see Section S2.4.).

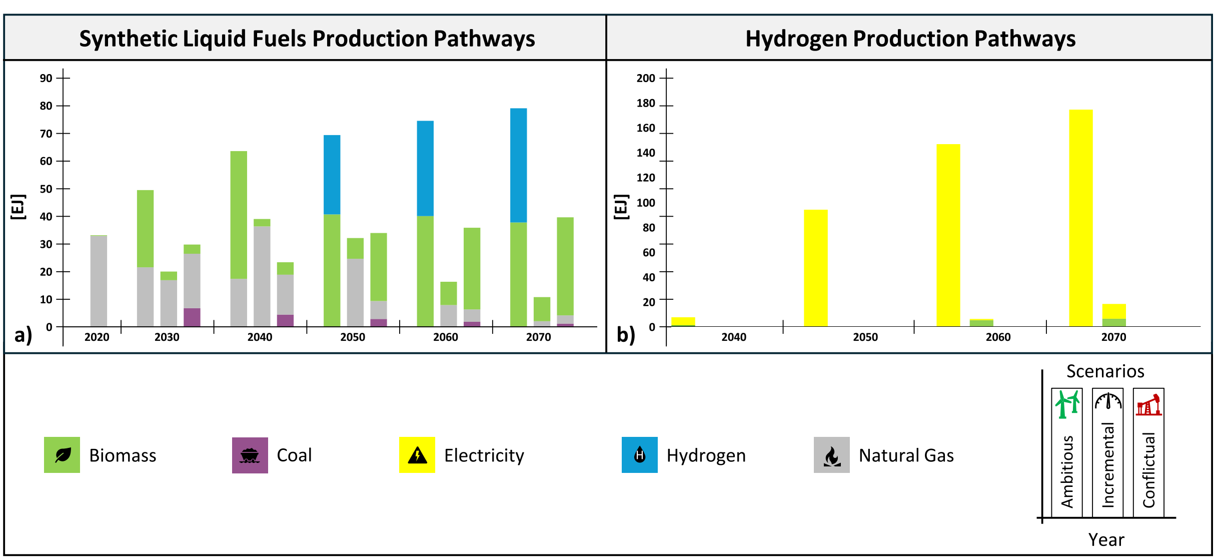

Fig. 10. Cost-effective fuel mix for the production of synthetic liquid fuels over the years and scenarios (graph a). As electrofuels, synthetic liquid fuels present a demand for hydrogen, which itself can be produced based on different energy sources (graph b). For years 2030–2070, the three bars present the result for the three scenarios representing, from left to right, the Ambitious, Incremental, and Conflictual scenarios, respectively. Hydrogen production is presented from the year 2040, as it is the first modeling timestep that shows hydrogen supply (associated with demand for heavy-duty road vehicles experienced in the Ambitious Scenario). In the Incremental Scenario, hydrogen production is not directed towards electrofuel synthesis but is instead assumed to be used directly as an energy carrier in heavy road transport and aviation.

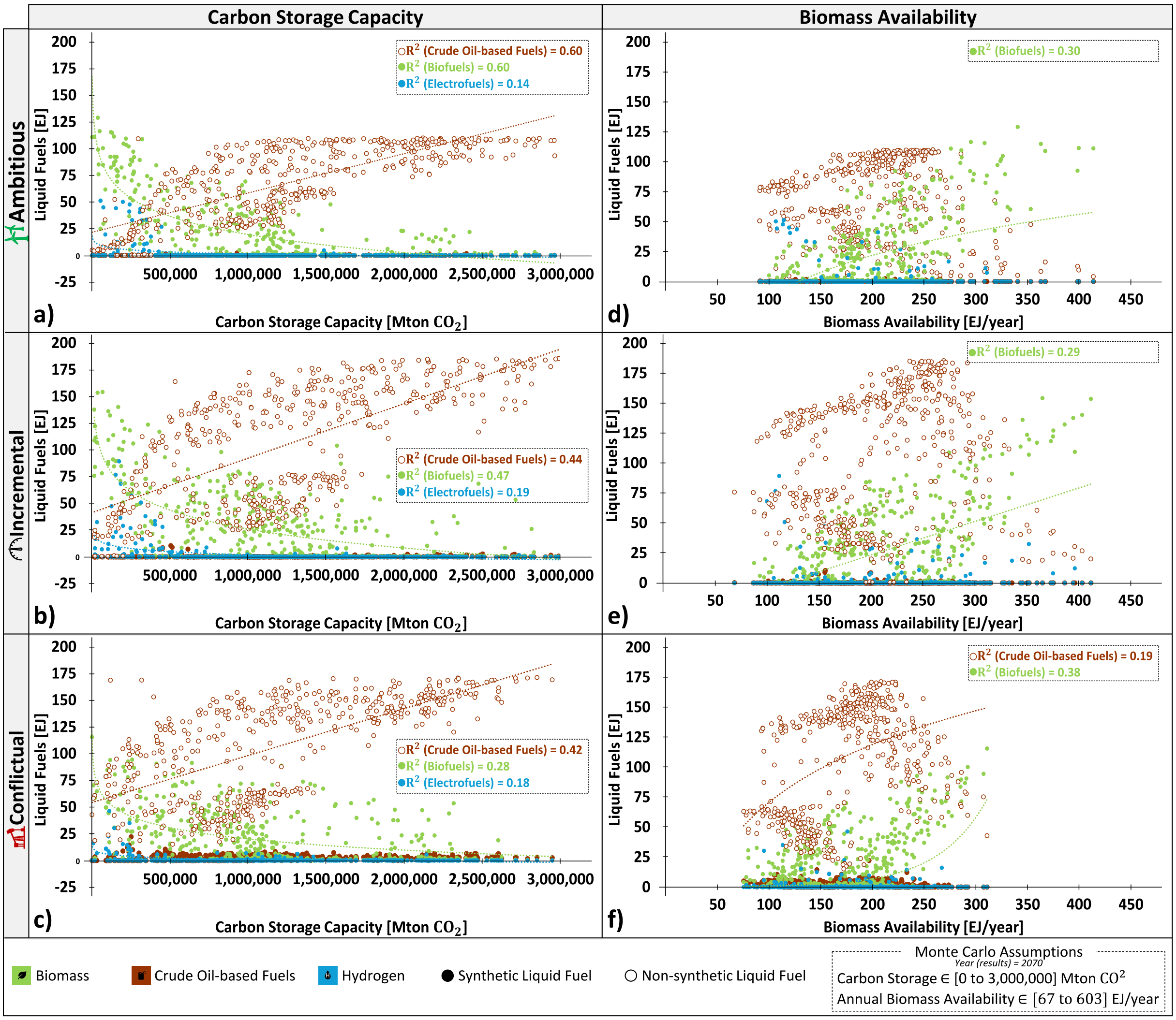

Fig. 11. Monte Carlo analysis results for the year 2070, showing parameters with an R^2 above 0.1. Graphs a–c present the impact of varying carbon storage capacity on liquid fuel use across the three modeling scenarios, while graphs d–f show the impact of varying annual biomass availability. Liquid fuels include both crude oil-based fuels (white circles outlined in brown) and synthetic liquid fuels produced via different pathways (colored dots). Trendlines are shown only for correlations with R^2 values above 0.1. Carbon Storage Capacity is tested as a lump sum of the three considered CCS technologies (i.e., Carbon Captured from Flue Gases from the Combustion of Fossil Fuels (CC), Bioenergy with Carbon Capture (BECC), and Direct Air Capture (DAC). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In 2070, crude oil–based fuels show a positive correlation with carbon storage capacity, with R^2 values ranging from 0.42 to 0.61, and the strongest effect is observed in the *Ambitious Scenario*. This indicates that carbon storage capacity is a key enabler for a continued use of crude oil-based fuels, particularly when stricter climate targets would otherwise restrict fossil fuel use. In contrast, synthetic liquid fuels are less dependent on carbon storage capacity, as they mainly serve to substitute crude oil in hard-to-abate sectors rather than replacing oil use in stationary energy and road transport, where other options are more cost-effective. Bio-based synthetic fuels also show a notable correlation with carbon storage, with R^2 values ranging from about 0.28 to 0.60. This correlation strengthens under more stringent climate targets in the *Ambitious Scenario*, as additional carbon storage capacity reduces the need to expand biofuel demand. Electrofuels, however, remain comparatively insensitive to carbon storage capacity. As shown in the base case results, electrofuels deployment is driven primarily by the stringency of carbon budgets, rather than the storage availability.

In contrast, biomass availability was found to primarily affect synthetic liquid fuels, particularly when produced as biofuels, with R^2 values ranging from 0.29 to 0.38. The strongest correlation was observed in the *Conflictual Scenario*. This reflects that under limited trade conditions, resources are used regionally, making bio-based synthetic liquid fuels demand highly sensitive to regional availability. Still in the *Conflictual Scenario*, crude oil-based fuels also showed a correlation above 0.18. This trend is explained by its looser climate targets, which continue to favor crude oil-based fuels. In this context, bio-based synthetic fuels do not act as a direct substitute for fossil fuels; rather, they serve as an additional supply option to cover new demand that exceeds regionally available crude oil. Therefore, under looser climate targets, regional resource availability supports the continued use of crude oil-based fuels, which remain the first choice according to the system's merit order.

3.2. *Local energy port clusters adoption to a low-carbon transition: Future role of liquid fuels*

One pillar of this study lies in complementing global energy transitions with specific local knowledge and thus, understanding the low-carbon energy transition as context-specific. Accordingly, this study incorporates the local energy cluster perspective, supported by a three-phase stakeholder engagement process: Semi-structured Interviews, Workshop I, and Workshop II.

3.2.1. Local energy port cluster's low-carbon transition

Local energy port cluster's current operations are dominated by "*mainly liquid bulk*" products, handled by the activities of three main types of companies, namely refineries, storage companies, and bunker suppliers. These companies' dynamics are shaped by their target market, i.e., international or domestic. Specifically, refined "*energy products mostly go to the Nordics*" (i.e., Northern European market), and only one-third of the final products "*is consumed in Sweden*", and thus, supplies domestic demands. A similar international trend is also registered at the storage companies who shared that only "*5% of the total fuel is consumed in Sweden*", meaning that just a small amount of their volumes is allocated for the Swedish domestic market. Contrarily, bunker suppliers have a variety of customers and varying demand that can go locally, "*from Gothenburg*" to "*run between nations*", which makes it difficult to determine the international versus domestic share for their products.

During the semi-structured interviews, there was a shared understanding among participants that the primary driver of operations for the companies involved is "*first and foremost the transport sector*". Despite the expected structural shift towards a low-carbon future of the transport sector, these companies believe that transport fuels will remain their main consumer. In addition, stakeholders noted that a portion of current liquid bulk flows is managed by "*a number of retailers who can resell within their chains*" to other and non-transport related energy uses, e.g., national strategic oil reserves, commercial opportunities, heating oil, lubricants, and fuels for combined heat and power (CHP) plants.

3.2.2. Future role of liquid fuels: Key enablers and barriers

A key point discussed with stakeholders was their view on the different SSPs and their narratives. As presented in Section 2, this discussion contributed towards the identification of three *Representative SSPs*, as those SSPs that were perceived as potentially leading to major shifts in the structure of the local energy cluster.

According to the strict climate ambitions of SSP1, the participating actors reflected on the ongoing shift in consumer strategies from crude oil–based energy systems towards increasing electrification. In this context, stakeholders broadly agreed on a potential and "*natural decrease in volumes*" of liquid bulk. This expectation was supported by several factors, including the "*conviction about electrification of the transport sector in general, from cars to trucks to partly ships*" and "*energy efficiency improvements*", both leading to reduced demand for liquid fuels. Nonetheless, stakeholders also reflected on the possibility of a future aligned with the SSP3 narrative. As illustrated in SPP3, the stakeholders could foresee that the energy systems "*will have liquid fuels for a long time*", a belief that supports a continued demand for these energy carriers, particularly from hard-to-abate sectors and from global markets, where road electrification, while advancing in Northern Europe, may remain less widespread.

Reflecting on the responses stated from the participatory interactions, stakeholders acknowledged both the urgency and their commitment to contribute to a low-carbon energy transition, considering that "*change becomes more powerful when the willingness to change comes from the company itself*". At the same time, considerable uncertainty remained regarding the future role of liquid fuels. This uncertainty grew stronger in discussions about how different potential roles for liquid fuels might affect the dynamics of the local cluster, underscoring the importance of assessing their future relevance to better "*adapt the business around*". Such an assessment was viewed as essential for understanding how the low-carbon transition may unfold at the cluster level, and for clarifying (i) whether "*today's infrastructure can have also a role in the future*" and thus, continuing to process, manage, and transport large volumes of liquid bulk through the local energy port cluster's quays; and (ii) the scale and target markets of such operations and thus, highlight if there is a need for "*the market looking for new energy carriers for both current and future fuel production*".

Through discussions between the research team and stakeholders, several factors were identified as either enabling (i.e., in this study referred to as enablers) or challenging (i.e., in this study referred to as barriers) a low-carbon energy transition at the local level, while also shaping the future role of liquid fuels. Overall, both the transition itself and the continued demand for liquid fuels were seen as primarily market-driven. Such a statement is grounded on the stakeholders' reflections that "*nothing happens just because it is better for the environment, but it must be better for the business*". In line with this, stakeholders further highlighted that future energy systems will account for "*facilities that will still need liquid fuels*" and thus, consumer demand is the principal mechanism behind a market-driven dynamic. At the same time, any sustained demand for liquid fuels would need to adapt to climate ambitions, shifting away from crude oil-based towards alternative production pathways that secure "*new liquid environmentally friendly products*". In the long term, this adaptation might be seen as a "*cost-benefit*" to the local energy port cluster. Accordingly, such long-term adaptation might become an economic driver, supporting both the low-carbon energy transition and the evolving role of liquid fuels. Such demand could also open new market opportunities – e.g., synthetic liquid fuels – guaranteeing the local energy port cluster to be a pioneer in the field by establishing the "*first network*" of these energy carriers, with potential benefits for exports and national energy security.

Although economic factors may act as a driver for continued liquid fuel demand, they were also widely seen as a barrier. The market for liquid fuels that comply with climate ambitions remains immature and with high fuel costs, making the fuels non-competitive compared to other strategies. The niche trend related to low-carbon liquid fuels might be maintained throughout the future, as "*what hinders alternative fuels' development is the low oil price*". Accordingly, the lack of cost-competitiveness stems partly from the absence of suitable infrastructure, shortage of raw material, as well as from uncertainty around future demand regarding both expected volumes and target markets. Stakeholders further noted that the absence of "*right policy and the right incentives*" to support low-carbon liquid fuel strategies poses an additional challenge for the energy transition at the local port cluster, and therefore for the future role of liquid fuels. In light of such reflections, the local energy port cluster highlighted that policy instruments are key and should be based on "*regulations that allow a rational climate mitigation, but support related businesses*".

Both enablers and barriers identified by the local energy port cluster were found to be aligned with the ten low-carbon key strategies to be applied at European ports and potential impacts of their application, as identified by DNV [106].

3.2.3. Local energy port cluster's low-carbon initiatives

Within the local energy port cluster, there is consensus "*that it is important to be involved and influence*" a low-carbon transition. Consequently, many stakeholders shared their ongoing commitments to a low-carbon transition at the company level. These commitments were reflected in the proactive approaches adopted by several of the organizations represented. As a result, several companies stressed that they were already performing beyond current legislative requirements, particularly regarding low-carbon targets, thus acknowledging themselves as actively contributing to the development of future low-carbon regulatory frameworks.

As summarized in Fig. 12, most stakeholders highlighted a variety of initiatives aimed at promoting low-carbon strategies (see the column "*Stakeholders' Participation – Stated Responses*" in Fig. 12). Many of these initiatives suggest that the transition of the local energy port cluster towards a low-carbon future might be primarily driven by strategies supporting continued liquid fuel demand. In this regard, stakeholders described how different low-carbon liquid fuels, including alternative fossil-based fuels and synthetic fuels (both biofuels and electrofuels), are being piloted or scaled in the participating port cluster. While liquid

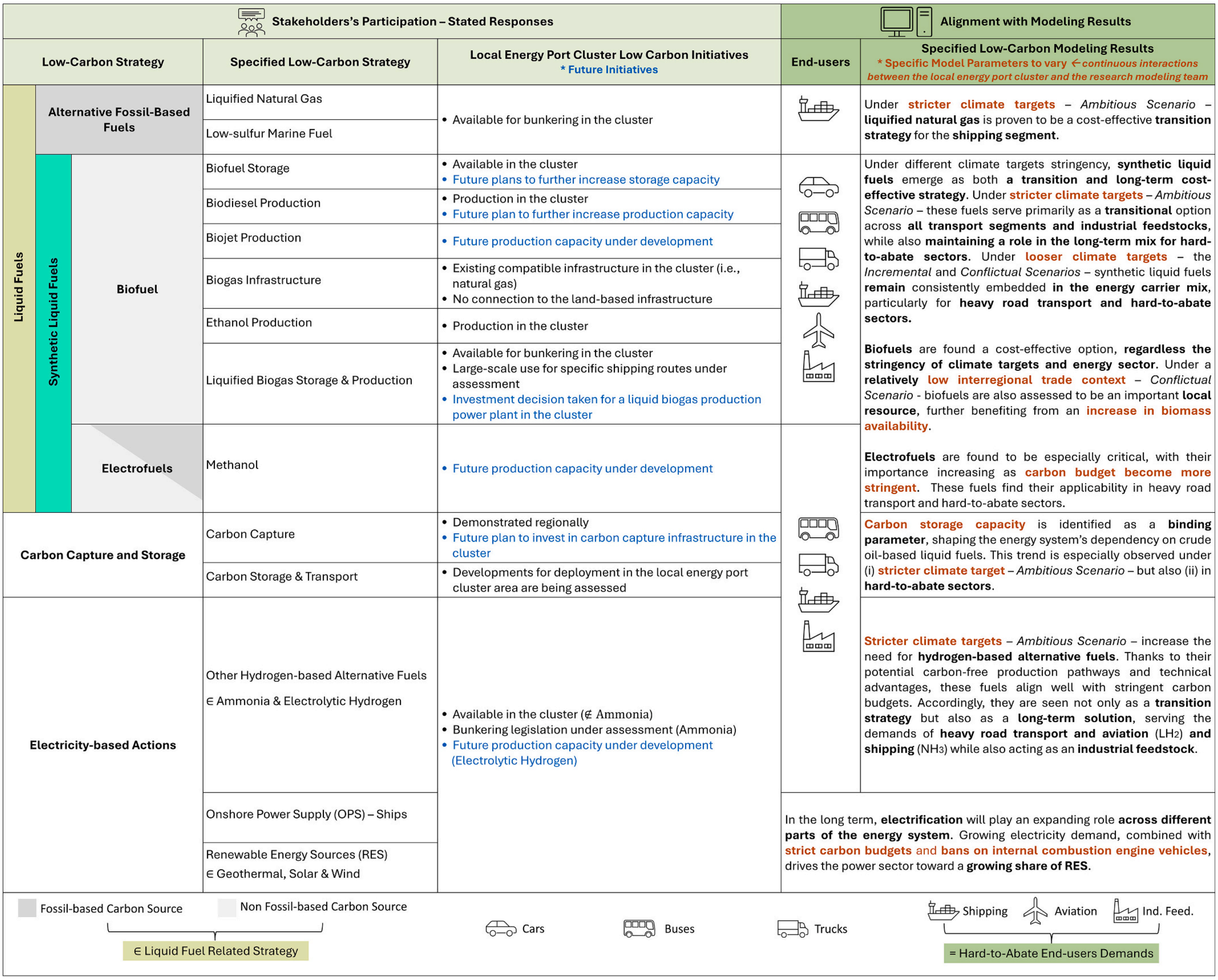

Fig. 12. Current and future announced (blue font) low-carbon action plans identified at the local level of the energy port cluster (light green), as well as the alignment of these initiatives with the GET modeling results (dark green). The action plans have a direct focus on liquid fuels, yet strategies with indirect influence on the role of liquid fuels were also mentioned during participatory interactions and therefore summarized in the table. Within the liquid fuels, strategies including both fossil-based (dark grey) and non-fossil-based (light grey) carbon sources were discussed. In the Supplementary Material, local stakeholders' outcomes are thoroughly presented in Section S1. Only end-users (i.e., road transport, shipping, aviation, and industrial feedstock) in focus in this study were included in this assessment. Column "Alignment with Modeling Results" is based on the GET model outcomes as presented in Section 3.1. The "Specified Low-Carbon Modeling Results" column highlights, in bold orange font, which of the specific model parameters to vary, those that were collaboratively identified by the research modeling team and stakeholders' participation, shaped a given low-carbon result. Ind. Feed., Industrial Feedstock; LH_2, Liquified Hydrogen; OPS, Onshore Power Supply; NH_3, Ammonia; RES, Renewable Energy Sources. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fuels were a central focus, other strategies were also mentioned, with carbon capture and storage as well as electricity-based actions emerging as crucial for the long-term low-carbon transition, particularly in hard-to-abate sectors.

It was possible to observe an alignment between the energy systems modeling and the views of the stakeholders. As most of the products refined within the port cluster are directed towards the transport sector (see Supplementary Material S1.2.2.), Fig. 8 and Fig. 9 provide, at a global scale, a representation of this local cluster's specific context. In particular, the results for hard-to-abate sectors (Fig. 9) align closely with the views expressed by participants regarding the continued importance of liquid fuels (see, e.g., Fig. S2 in the Supplementary Material). However, some of the stakeholder statements may appear to diverge from the model results. For example, local stakeholders reflected that, by 2050, "*declines of 70-75% in Europe*" could be registered in liquid fuels in road transport, whereas Fig. 8 shows that, compared to 2020, such a decrease might not exceed 60% (*Ambitious Scenario*). When hard-to-abate sectors are also considered, model results suggest that such a decrease does not surpass 9%, as shown Fig. 7 for *Ambitious Scenario.* These differences can be understood by the coverage of the two perspectives. Global ESOM includes a representation of hard-to-abate sectors, especially industrial feedstock, an aspect not considered by the local cluster. Similarly, GET model assumes a global scale, whereas participants' perspectives were shaped by a Northern European context, reflecting regional regulations and policy goals that are not always representative of the global context assumed in the model.

Fig. 12 further illustrates how the local perspective of the participating energy cluster (including mapped initiatives), not only confirms, but complements the global modeling insights, both pointing to a continued role for liquid fuels in a low-carbon transition. In brief, combining both GET results (see Section 3.1) with stakeholders' stated responses (see the column "*Stakeholders' Participation – Stated Responses*" in Fig. 12 and Fig. S1 in the Supplementary Material) show that while alternative liquid fossil-based fuels can act as cost-effective transition options, synthetic liquid fuels remain central across all scenarios, particularly for heavy transport and hard-to-abate sectors such as aviation and industrial feedstock. Within synthetic liquid fuels, electrofuels were highlighted as more interesting as climate targets become more stringent (both in the view of the local energy cluster and in the modeling results). Local stakeholders also shared carbon capture ongoing initiatives. Similarly, GET modeling results tested the impact of different carbon capture technologies and storage potential on the energy systems' dynamics. Results, moreover, revealed a broader local and global energy trend pointing to increasing electrification and renewable energy expansion, with a direct impact on all end-users' energy demand.

4. Discussion and Conclusions

This study investigates the future role of liquid fuels in a transition to low-carbon energy systems by merging global energy systems modeling with the participation of stakeholders representing a local energy port cluster. Through this continuous interaction, this study bridges the gap between global long-term cost optimization modeling exercises and real-world perspectives of actors involved in the liquid fuel energy transition.

Generally, the GET modeling results (Section 3.1) suggest that liquid fuels will continue to play a role in both transport and industrial feedstock energy mixes over a long-term span. For transport and industrial feedstock (see Fig. 7), modeling results, moreover, suggest that there might be a continued use of crude oil-based fuels. From a cost-optimization perspective, this outcome reflects the model's comprehensive representation of different energy sectors and their cross-sectoral interactions. Accordingly, phasing out coal-based electricity and heat emerges as the most cost-effective strategy, opening up for a prolonged era of crude oil-based fuels for transport, while still meeting the global climate targets. Only under stricter carbon budgets (i.e., *Ambitious Scenario*) does the model identify it as economically viable to accelerate the shift from crude oil-based fuels in other sectors, such as transport and industry. According to the GET results, these sectors' demand for synthetic liquid fuels is expected to increase around three times by 2030, compared to 2020. Despite the gradual shift away from crude oil-based fuel, GET modeling results indicate that, in all scenarios, liquid fuels may remain important in the low-carbon transition, regardless of the carbon budget (see Fig. 7). This is particularly the case in sectors that are difficult to electrify (see Fig. 9). Liquid fuels' continued role depends on a shift from fossil-based fuels to synthetic alternatives produced through non-fossil pathways (see Fig. 10).

Stakeholders in the local energy port cluster also envisioned a continuing role for liquid fuels in a low-carbon transition, as indicated by some of the low-carbon initiatives in the port (e.g., future initiatives on local electrofuel production capacity as presented in Fig. 12 and Fig. S1 in Supplementary Material). Their views expanded on the modeling results by highlighting how the viability of the liquid fuels depends on economic conditions, infrastructure availability, market dynamics, and policy contexts. From a long-term perspective, liquid fuels could benefit from favorable economic and market developments. If a local energy port cluster adapts quickly to potential future demand for liquid fuels, it may secure a strong market position and support the maturation of alternative liquid fuel technologies. This, in turn, could reduce associated costs, generate export revenues, and strengthen national energy security. At the same time, stakeholders acknowledged challenges, including the niche status of alternative liquid fuels, the lack of infrastructure within the whole supply chain, particularly for synthetic liquid fuels, and limited policy support. The stakeholders involved stress the importance of targeted policy instruments that encourage adoption on both the supply and demand sides, for these energy carriers. Thus, the mapping also highlights the importance of policy instruments in shaping the role of liquid fuels.

4.1. Comparison with previous studies

Consistent with previous research (e.g., [11–32]), this study finds that liquid fuels, especially those synthetically produced, are likely to retain a central role in future energy systems. The importance of synthetic liquid fuels increases under more stringent climate targets, as they are well-suited to the operational demands of energy-intensive, hard-to-abate sectors, especially aviation and industrial feedstock (see Fig. 9).

The modeling outcomes are consistent with existing state-of-the-art research, which underscores the flexible role of synthetic fuels across different parts of the energy system. As previously advocated by Mustapha et al. [16], under low-carbon targets and biomass availability, both parameters tested in the *Ambitious Scenario*, biofuels are defined as a cost-effective energy carrier (see Fig. 10). Nonetheless, this study does not necessarily agree with Mustapha et al. [16], who argue that, under strict carbon budgets and high CO_2 taxes, biofuels are preferred over the use of solid biomass in the power and heat sector. This difference mainly stems from the comprehensive representation of alternative low-carbon energy carriers in GET for hard-to-abate sectors (see Fig. 9), allowing the system, under different carbon budgets, to allocate biomass to the power and heat sector and thereby accelerate the defossilization of these sectors.

Compared to the previously mentioned research, this study further expands the representation of synthetic liquid fuels, not only including biofuels, but also an electrofuel route. By doing so, it indicates that the cost-effectiveness of liquid fuels depends on their production pathways. Studies such as Bramstoft et al. [17], Lester et al. [18], Drünert et al. [19], Wassermann [23], and Zhao et al. [24] emphasize that the location and availability of biomass and renewable electricity largely determine the feasibility of synthetic fuel production. As tested in the *Ambitious Scenario*, GET results suggest that limited biomass availability is combined with high shares of renewable energy (see Fig. 6) and thus, low marginal electricity costs, further support the deployment of synthetic fuels, particularly electrofuels (see Fig. 10 graph b). Such an insight has previously been discussed by Victoria et al. [25] and Jordan et al. [26]. These authors also argue that under strict carbon reduction goals, synthetic liquid fuels are especially applicable to hard-to-abate sectors, a trend also captured in this study (see Fig. 9). Similar perspectives on the potential future demand for synthetic liquid fuels emerged during stakeholder interactions, where local energy port cluster actors noted their ongoing efforts to expand local biofuel and electrofuel production and use capacity.

Blanco et al. [14], Lehtveer et al. [15], and Catania et al. [33] argue that electrofuels are cost-competitive mainly under conditions of limited biomass, restricted CCS deployment, or ambitious climate targets. These findings are aligned with the Monte Carlo analysis (see Fig. 11) in this study, which identifies carbon storage capacity and biomass availability as critical constraints in assessing liquid fuel pathways. As tested in the *Ambitious Scenario,* synthetic liquid fuels gain greater relevance when carbon storage is constrained (see Fig. 11 graph a). Conversely, abundant biomass availability sustains high demand for bio-based synthetic fuels, particularly in the *Conflictual Scenario* (see Fig. 11 graph f), where cost advantages arise from leveraging regional resources.

Millinger et al. [20,22,32], Aliabadi et al. [27], Mignone et al. [28], and Law et al. [31] reflect upon the complementary role that biofuels and electrofuels may have, arguing that each represents a suitable alternative when the other is constrained. This study further complements these views by examining how the composition of synthetic liquid fuels changes under different binding parameters, namely carbon capture and storage capacity and biomass availability (see Fig. 11). This pattern is particularly evident under conditions of low biomass availability and stricter carbon budgets (see Fig. 11 graph d and graph e), where, at lower biomass availability, electrofuels satisfy a higher share of the synthetic liquid fuels demand, compared to biofuels. Under tighter carbon targets, a Monte Carlo analysis shows that greater carbon storage capacity reduces the reliance on electrofuels, as it enables the continued use of crude oil-based liquid fuels. These results can be explained by the fact that, under such circumstances, carbon sequestration required to offset the extended use of crude oil-based fuels, outcompetes carbon utilization as feedstock for electrofuels, consistent with arguments previously presented by Chyong et al. [29] and Wulff et al. [30].

Brynolf et al. [21] argue that bio-electrofuels are both economically and environmentally viable. Despite bio-electrofuels not being directly represented in this research, GET modeling findings are in line with the referred study, especially with the *Incremental* and *Conflictual Scenarios*, in which synthetic liquid fuels are predominantly produced from biomass (see Fig. 10 graph a). The modeling results are also consistent with the revealed preferences of stakeholders in the local energy port cluster, who favor short-term investments in biofuels. At the same time, there is broad agreement that additional policy incentives are needed to satisfy hydrogen-based demand and ensure its cost-competitiveness.

4.2. Reflections on a continuous interaction between global energy systems modeling and local energy port cluster participation

The present study expands on existing research by examining how different socio-economic trends and local knowledge influence the role of synthetic liquid fuels and their production pathways across modeling scenarios.

While recognizing that ESOMs and qualitative stakeholders' participation are two meaningfully distinct perspectives, this study integrates them into a single analytical framework as an effective way to explore the future role of liquid fuels. According to this framework, both global modeling outcomes and local stakeholder perspectives are suggested to agree that liquid fuels may retain a role in a low-carbon society. Nonetheless, this study argues that these perspectives do not simply confirm each other but are complementary. This complementarity arises because each perspective motivates the role of liquid fuels differently. Based on the GET model, liquid fuels are often identified, despite the strictness of carbon budgets, as the most cost-effective solution. Although agreeing that economic aspects are critical, stakeholders view the continued use not necessarily as a response to strict climate targets, but more as largely driven by market structure and policy landscape that sustain their demand. Accordingly, this study reasons that a continuous interaction between these two perspectives provides a more holistic understanding of the energy system. An effective transition must therefore consider not only global or national targets but also the specific needs and characteristics of local energy systems.

In brief, this study acknowledges that presenting and discussing modeling results is standard practice in energy systems modeling. However, reflections on how stakeholders' participation can be integrated into energy systems models remain limited in literature. Accordingly, one novel contribution from this study, to the ESOM community, is the explicit description of the analytical framework showing how a dialogue between energy modelers and local actors can be mutual beneficial, where actors can help refine modeling uncertainties and model results can guide local actors towards low-carbon, long-term transitions.

4.3. Limitations and future work

While the main finding suggests a continued demand for liquid fuels, several uncertainties remain, which could be addressed in future research.

Stakeholders may express preferences inconsistently, often influenced by specific priorities rather than a holistic view, making their reasoning somewhat of a “black box”. Their input may focus on narrow topics and translating their preferences into conceptual, or quantitative data, can be challenging. To address these issues, this study fostered a continuous interaction throughout all phases of the research, enabling dialogue, clarification, and in-depth exploration of responses.

The local energy port cluster involved in this study represents a Swedish case and given the context-dependent nature of low-carbon transitions, findings linked to the port cluster may not be directly transferable to other regions. Future work could expand stakeholders' participation to include energy port clusters worldwide, ensuring broader perspectives.

Energy security has often been assessed as a key pillar in energy discussions. Although the participating stakeholders did not highlight it as a main concern, the narrative of the *Conflictual* Scenario, with the restricted interregional trade, favoring regional resources, may influence a port's core business as being a hub for traded goods including liquid fuels. This relationship, however, warrants further investigation.

While energy systems models provide valuable insights into the future evolution of energy systems, they typically simplify system representation, often assuming: (i) price-inelastic demand; (ii) cost-based optimal decisions that overlook intangible investment factors; and (iii) perfect foresight. Albeit their simplified system representations, energy system models are key for generating coherent outcomes based on specified assumptions. In the context of this study, when combined with insights from stakeholders in the local energy port cluster, the GET model was key to demonstrating that under different socio-economic narratives, there may still be a future role for liquid fuels.

To conclude, this study demonstrates that the use of liquid fuels will likely be maintained in future. However, the future role of synthetically produced fuels, such as biofuels and electrofuels, may depend on socio-economic pathways and local initiatives. The stakeholders' perspective adds value to the study, considering their local knowledge of the context under transition.

CRediT authorship contribution statement

Maria de Oliveira Laurin: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rasmus Parsmo:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Oskar Johansson:** Writing – review & editing, Methodology, Investigation. **Maria Grahn:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Julia Hansson:** Writing – review & editing, Methodology, Conceptualization. **Fayas Malik Kanchiralla:** Writing – review & editing, Methodology, Investigation, Data curation. **Mariliis Lehtveer:** Writing – review & editing, Methodology, Investigation. **Selma Brynolf:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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201494) and TRV 2024/35280 (STORM project); (v) and the Swedish Foundation for Strategic Research, grant agreement FID20-0014. Moreover, we would like to thank the Port of Gothenburg for financial support and especially Jill Södervall and Lena Lilienberg for guiding us in how an energy port operates.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2026.127640.

Data availability

Supplementary Material was attached to my submissions. Most of the data is presented in the Supplementary Material. The code referring to the used model can be further shared upon request

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