The entanglement of society and technology in the debate over sustainable fuels and chemicals.

An analysis of socio-technical cross-cutting challenges in SUNER-C

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Executive summary

This report has as goal the identification of important cross-cutting socio-technical challenges related to the SUNER-C technology choices. The term "cross-cutting socio-technical challenges" refers to a whole set of social, economic, organizational, environmental and other disciplinary factors that influence the development and deployment of technologies. Based on in-depth interviews and conversations with expert stakeholders, as well as meeting observations, the report first inductively identifies five different visions of the future of sustainable fuels and chemicals. Each vision is analysed on the basis of its framing of challenges and solutions, its proposed technologies and material settings, its knowledge inputs and outputs, the governance and institutions it needs, and the actors that support it. The five visions are:

- Vision 1 – Anticipating the direct conversion of solar light into fuels and chemicals
- Vision 2 – Hand in hand: electrification and multistep conversions to synthetic fuels and chemicals
- Vision 3 – Being agnostic to the technology to reach shared carbon emission reduction goals
- Vision 4 – Prioritising renewable energy and electrification
- Vision 5 – Building a just and electrified energy future

A comparative analysis then allows for the identification of cross-cutting socio-technical challenges across these visions. For some challenges there seems to be convergence about how to approach them in the different visions, but often the challenges may be identical, while the way to approach them is quite different. The reason is that behind the different visions of technology are different choices about investments, infrastructure needs, research priorities, value chains, organisation of the energy system, distribution of costs and benefits, political choices and policy priorities, and, in the end, very different societies. The main cross-cutting issues identified are:

- For the framing of challenges and solutions: climate change; energy security; affordability of the transition; the (growth in) demand for energy, fuels and chemicals; the source of (renewable) energy and carbon; the role of imports; the application of sustainable fuels and chemicals.
- For knowledge: the role of science; the role of societal knowledge and stakeholders.
- For technologies and materials: the choice of central technologies; the end-use or application of sustainable fuels and chemicals.
- For governance and institutions: the policy framework; the innovation model.

The analysis shows how scientific and technological innovations are always influenced by and entangled with societal, economic, political and cultural evolutions and needs.

Science and technology indeed shape a society, but simultaneously societal concerns, ambitions and values also shape science and technology. This two-way dynamic is usually referred to as co-production, and it is a central tenet of this report. According to the co-productionist model of innovation, the trade-offs between the societal implications that are manifested in technology decisions should not be made by technology-developing research and industry alone, but should be made in open dialogue and with input from policy-makers, societal stakeholders like unions and NGOs, and a broad pallet of multi-disciplinary knowledge.

The analysis has several implications for the SUNER-C project. Since the 'technological approaches' of SUNER-C are, in fact, socio-technical visions in which societal choices are continuously made, this finding can form the basis for a deeper debate about sustainable fuels and chemicals in the current SUNER-C community. It is necessary to create spaces for acknowledging and discussing the widely diverging visions and the mentioned cross-cutting issues, and for investigating how they can be translated into the different work packages. The report presents a preliminary version of a Conversation Tool to facilitate such a debate. The findings should also inform the thinking in SUNER-C about a possible follow-up in a Large-Scale Research and Innovation Initiative and how this can ensure better integration of societal questions and of societal stakeholders. There are widely varying pathways to a future energy system (and to the production of sustainable fuels and chemicals), that all involve massive challenges and investments, which implies that from a societal perspective a selection process will be necessary. This process is something that should be done in ongoing, interdisciplinary debate by different stakeholders and 'knowledge holders'.

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List of abbreviations

List of abbreviations	
CSA	Coordination and Support Actions
C&D	Communication and Dissemination
D	Deliverable
H2020	Horizon 2020
IAB	International Advisory Board
IEA	International Energy Agency
KPIs	Key Performance Indicators
LSRI	Large-Scale Research and Innovation Initiative
MI	Mission Innovation
NGOs	Non-Governmental Organisations
RTOs	Research and Technology Organisations
R&D	Research and Development
R&I	Research and Innovation
SMEs	Small and Medium-Sized Enterprises
SRIA	Strategic Research and Innovation Agenda
WP	Work Package

1 Introduction

1.1 SUNER-C

The overarching objective of the SUNER-C project is to create an inclusive innovation community and eco-system that builds on the current SUNERGY network and includes new stakeholders across Europe. Bringing together fundamental and applied knowledge from various sectors of society as well as often unique resources, the enhanced community will prepare a Large-Scale Research and Innovation initiative (LSRI) beyond the CSA, as a partnership or another instrument to be discussed and agreed upon with the Commission and the Member States and Associated Countries. The goal is to overcome scientific, technological, organizational, and socio-economic challenges, accelerate innovation in solar fuels and chemicals, and enable the transition of existing and future technologies from laboratory and demonstrator levels to large-scale industrial and broad societal applications.

Through a holistic approach, SUNER-C will contribute to a circular economy by replacing fossil-derived fuels and chemicals with renewables and carbon recycling as a key element toward the EU net-zero emissions target by 2050. SUNER-C will build upon the work of SUNERGY, a pan-European initiative on fossil-free fuels and chemicals from renewable power and solar energy, with currently over 300 supporting organizations across and beyond Europe to date.

Figure 1 is an overview of the work package structure of SUNER-C with its eight WPs. The deliverable D6.1 "Identification of important socio-technical cross-cutting challenges and relevant stakeholders" is a deliverable of WP6 "Socio-technical and cross-cutting aspects".

Please see here https://sunergy-initiative.eu/suner-c-project/ for more information.
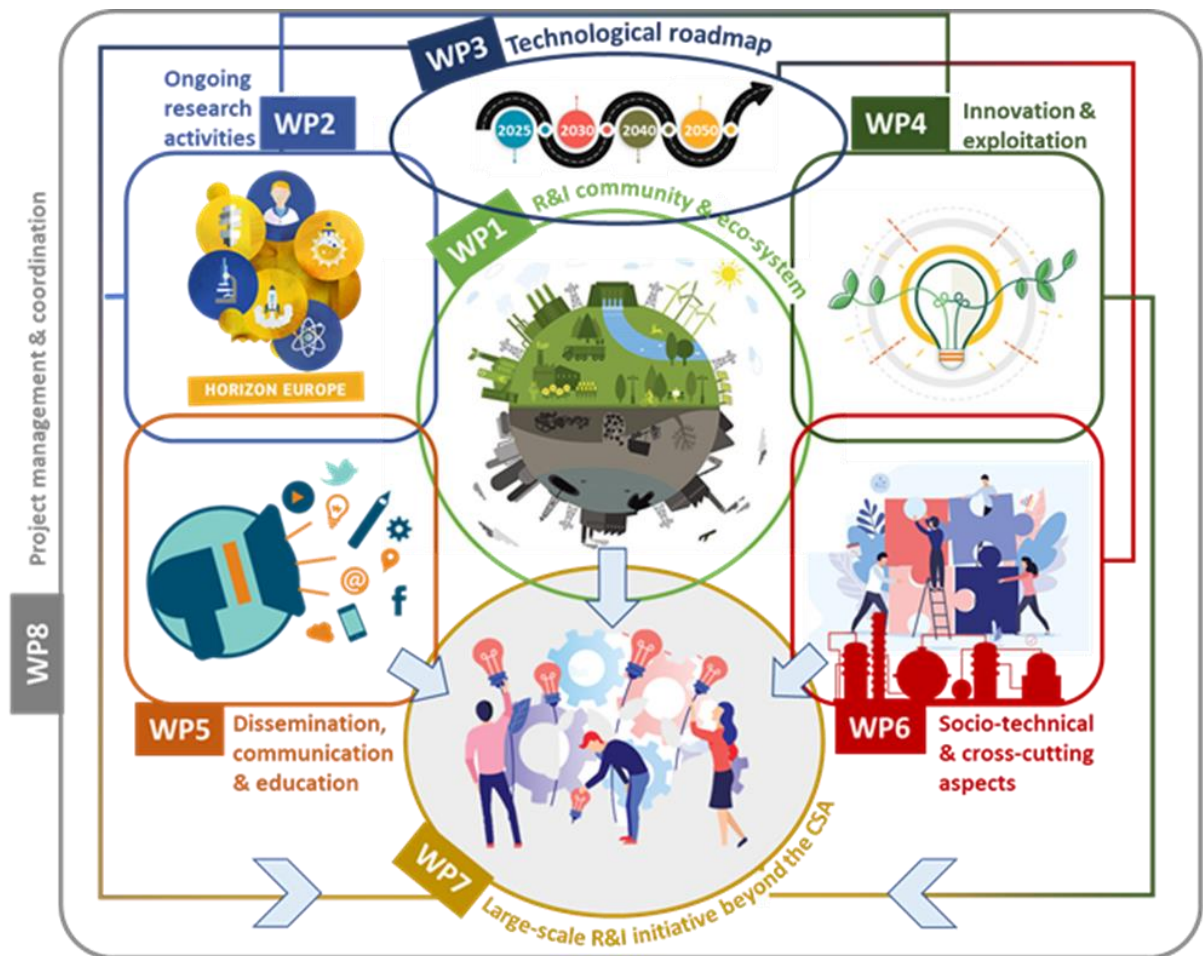
Figure 1: SUNER-C CSA project and its eight work packages.

1.2 The objective and approach of this deliverable

Work Package 6.1. of the SUNER-C project has as objective the identification of important cross-cutting socio-technical challenges related to the SUNER-C technology choices. The term "cross-cutting socio-technical challenges" refers to a whole set of social, economic, organizational, environmental and other disciplinary factors that influence the development and deployment of multiple technologies. Examples include social challenges (e.g. distribution of costs and benefits across social groups), environmental challenges (e.g. effects on resource use and emissions), legal challenges (e.g. translation of policy into law and regulations), governance challenges (e.g. who decides and who is left out?) or ethical challenges (e.g. the acceptability of risks).

The way of addressing the identification of these challenges in WP6 has the ambition to go beyond the traditional 'societal acceptance' approach of technology. In strongly technology-driven projects such as SUNER-C, one sometimes tends to fall in a typical technology push model of innovation. In this model, innovation starts in the laboratory

of the scientist or the R&D department of companies, and then finds its way to market applications. The role of governments is mainly to provide funding for research and experimentation, as well as creating a supportive regulatory framework. The idea of 'societal acceptance' fits nicely in all of this: all other societal actors are essentially passive recipients of technology, and mainly have to be warmed up to become receptive to the technological innovations. Cross-cutting challenges would then mainly refer to factors that can convince or force societal actors to start using the technology,

However, studies in the field of science, technology and innovation have amply shown that this is a far too simplistic picture of how innovation happens (Chilvers et al., 2021). Scientific and technological innovations are always influenced by and entangled with societal, economic, political and cultural evolutions and demands. Science and technology indeed shape a society, but simultaneously societal concerns, ambitions and values also shape science and technology (MacKenzie & Wajcman, 1999; Sismondo, 2010). This two-way dynamic is often referred to as co-production.

The concept of co-production is central to this report (Jasanoff, 2015). According to the co-productionist model, the trade-offs between these societal implications that are manifested in technology decisions, should not be made by technology-developing research and industry alone, but should be made in open dialogue and with input from policy-makers, societal stakeholders like unions and NGOs, and a broad pallet of knowledge [1]. Recognising this dynamic of co-production becomes all the more important in turbulent times. The sustainability ambitions that the European society has set for itself by 2050 are enormous and will lead to deep societal changes. These ambitions constantly interact with ongoing, and as of yet unclear, geopolitical changes in relations with the rest of the world. Under these circumstances, the model that claims that innovations start in the 'neutral' environment of the lab (which never was neutral, anyway) and then spread out through markets, is outmoded. Instead, thinking from a co-productionist model teaches that technology development – and thinking about future visions and roadmaps for technologies – has to try to take the shifting societal context in account, try to be aware of societal needs and look at conflicts and controversies surrounding technologies, recognise the roles of different societal actors and their concerns surrounding technology development (such as who wins and who loses, who is responsible, who has a voice). In this model, societal actors are not passive; even if they do not 'make' technologies, they are actively involved in shaping the context and thinking about desirable futures; they voice concerns; they have their own interests; they may have different ideas and

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[1] A famous example where a technology push policy failed due to lack of alignment with user needs/demands, is the case of the Concorde plane. Although the plane was really fast, it also made too much noise and consumed too much fuel, making it too costly. This resulted in huge financial losses, even before the crash in 2000.

experiences about what works; they have their own knowledge and expertise about what is relevant.

What does all of this mean for the identification of societal, cross-cutting challenges related to SUNER-C?

One of the main implications is that these challenges no longer simply relate to removing barriers for societal acceptance of sustainable fuels and chemicals. Instead, it becomes necessary to analyse and take into account the considerable debate that exists about what exactly sustainable fuels and chemicals are, how they should be sourced, with which technologies they should be developed, which role they have to play in the economy, which social and ecological impacts they have, and so on. In other words, the identification of societal challenges is closely connected to the vision one has of the future role and development of sustainable fuels and chemicals. This way of approaching cross-cutting challenges makes the analysis more complex – it is not about simply identifying and then removing a few barriers – but it should also inform more realistic, robust and democratic innovation processes[2].

To give a brief example: the Strategic R&I Agenda of SUNER-C considers two 'technological approaches' (SUNER-C, 2022, p. 2) to produce fossil-free fuels and chemicals for a climate-neutral Europe. One approach builds on a multistep conversion or indirect route, in which renewable energy is converted into chemicals and fuels through multiple steps. A second approach adheres to a direct route, in which solar energy is directly converted into solar fuels and chemicals. These technological visions presuppose different choices and assumptions about renewable energy, electrification, energy storage, decentralised or centralised energy systems, infrastructure, hydrogen's "colours" and transport, carbon capture and so forth. And these in turn have different implications for distribution of costs and benefits, for governance and policy instruments, for ownership and participation, for environmental effects, for jobs, for (in)dependence from third countries and so on. As already said above, according to the co-productionist model, the trade-offs between these societal implications should not be made by technology-developing research and industry alone, but should be subject of a societal debate.

Another way of understanding this is realising that a technology does not work in and by itself, but only functions as part of a broader socio-technical system (Geels et al., 2017; Köhler et al., 2019). Technology is always embedded in a network of actors (organizations) in the system, infrastructures, institutions – i.e. formal and informal 'rules of the game' - market circumstances, behaviour and practices of citizens, even values and cultural

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[2] There is quite some experience with such an approach in the field of Technology Assessment. See e.g. Grunewald (2009), van Est and Brom (2012), Rip (2015).

meanings regarding the technology. It is this configuration of elements that make a technology work.

What holds for a technology as in fact being part of a socio-technical system, is also true for a technological vision or roadmap: these are inherently socio-technical constructs (Konrad & Böhle, 2019). Future expectations of technology development are never 'just technical', but are always intertwined with societal choices: they assume or advocate specific ideas about e.g. the role of technology, science, markets, industry, government and citizens (Scoones et al., 2015). Moreover, when they serve as points of orientation for action (e.g. legislation, investments...), visions influence and shape political and social developments, which in turn shape technological developments (Berkhout, 2006).

Given all this, the objective of WP6 to identify societal, cross-cutting challenges, is advanced through the identification of different socio-technical visions about the role and future of sustainable fuels and chemicals, and their implications for society. Based on in-depth interviews and conversations with expert stakeholders, as well as meeting observations, we inductively identified five different visions of the future of sustainable fuels and chemicals in this report. These five visions contrast somewhat with the two technological approaches described in the SUNER-C SRIA. This contrast is not because actors identified other sets of technologies, but because there is considerable divergence in the importance and role they attach to different technologies and in the consequences associated with them.

The report proceeds as follows: the second section is a methodological section and describes the analytical tool and the methods we used to identify socio-technical visions. The empirical analysis is presented in the third section, identifying five diverse socio-technical visions. Section four consists of a concluding discussion and potential next steps for SUNER-C and, even more importantly, of its possible development into a Large-Scale Research and Innovation Initiative.

2 Methodology

2.1 Analytical tool

To explore how actors associated to high-level chemical and industrial projects, such as SUNER-C, interpret the future of sustainable fuels and chemicals, we use a framework that helps to map socio-technical visions (Longhurst & Chilvers, 2019).

Research on visions recognises that socio-technical visions are articulated to anticipate and justify change in the present (Berkhout, 2006). These projections of the future both represent and create pathways of change by shaping how problems are understood and which strategies help to address them (Granjou et al., 2017; Wyborn et al., 2020). In other words, visions are functional to actors in interpreting problems and solutions, in establishing and coordinating coalitions, and in pursuing their interests in processes of change. A particular actor's vision is a bid about what the future might look like and is positioned in the context of other actors' bids, initiating a course of action that may reaffirm or change previous trajectories. Accordingly, Berkhout (2006) defines visions as 'collectively held and communicable schemata that represent future objectives and express the means by which these objectives will be realised' (p. 302) and suggests that they consist of objectives, social and institutional relationships and technologies. Together, particular technical visions will thus bring forward specific political choices, which serve as a commitment to a particular course of action. Hence, visions are normative (i.e. they have a basis in values, norms and interests) and performative (i.e. they do something, such as influencing investment decisions, consumer behaviour or policy proposals).

Over the past years, the research on visions has been refined and adjusted, resulting in a framework to map socio-technical energy visions (Longhurst & Chilvers, 2019). We use the framework of Longhurst and Chilvers (L&C) to identify the different visions and to present them in a systematic way. In the original article, L&C state that visions can be analysed in different components, namely "meanings", "knowings", "doings" and "organisings". While we stick to the components, we have decided, however, to change these somewhat elusive terms and to add the component "actors", since this last component provides us with the opportunity to identify who is behind the vision (Berkhout, 2006). This brings us to the following framework to analyse the visions:

- **'actors'** refer to diverse groups representing government, science, business, and civil society, all actively involved in shaping visions of the future. The interaction between these actors, their interests, ideas, values and power relations will shape a (more or less) shared, common vision of the future.
- **'framings'** (the 'meanings' component of L&C) refer to the formulation of challenges, motivations, problems and potential solutions within socio-technical futures. In the context of the energy sector, examples include concerns like climate change, affordability for consumers, energy security, and economic justifications.
- **'knowledge'** (the 'knowings' component of L&C) refers to the knowledge inputs that influence and the knowledge outputs that result from socio-technical futures. Knowledge can derive from scientific research, but can also be based on experience or observation, or can be tacit; it can be qualitative or quantitative. In

the energy system, knowledge inputs originate from sources like modelling, scientific research, engineering, social sciences, or public awareness.

- **'technologies and materials'** (the 'doings' component of L&C) refers to the technological and material choices that are part of socio-technical futures. In the energy system, expectations often revolve around the future of renewable energy sources, fossil fuels, nuclear energy, and may also encompass elements like infrastructure and carbon capture, utilization, and storage (CCUS).
- **'governance and institutions'** (the 'organizings' component of L&C) refers to the methods of social and political organization, the explicit and implicit rules that guide this organization, as well as to the utilization of various regulatory, economic, or voluntary mechanisms in shaping the future. In the energy sector, this may include policies such as carbon rationing, energy pricing, or public information campaigns.

2.2 Methods

The analysis of the prevalent socio-technical visions for sustainable fuels and chemicals draws from thirteen recorded interviews, lasting 60-120 minutes each, and four in-depth conversations of approx. 60 minutes. Respondents were selected through purposive and snowball sampling (Yin, 2016), in which we focussed on maximising diversity across civil society, business and science and technology. The interviews focussed on the views and expectations related to SUNER-C, companions and opponents, problems, solutions and potential futures and, more generally, the components of our analytical tool. In the first part of the interviews, we were guided by the perspective of the interviewees, while, later on, we also inquired about alternative views. A similar but less structured approach was used in the conversations. Additionally, we took roles as participant-observers in 25 meetings and events related to synthetic fuels and chemicals, hydrogen and industrial transitions (see Appendix for an overview of the interviews, in-depth conversations and events we joined).

Regarding the analysis, the interviews and conversations were transcribed and coded, using a software programme and the components of the analytical framework. Over time, five ideal-typical visions consisting of *actors*, *framings*, *knowledge*, *technologies and materials*, and *governance and institutions* emerged inductively, which were outlined in a draft. The draft was then enriched by using the field notes of our participatory observations. Subsequently, this analysis was shared for feedback with our colleagues of WP6 and the interviewees. Overall, this led to the identification of five socio-technical visions, which are outlined in the following section.

3 Empirical analysis

This section presents the five different socio-technical visions about sustainable fuels and chemicals. For every vision, we describe the *actors*, *framings*, *knowledge*, *technologies and materials*, and *governance and institutions,* distinguishing similarities and tensions that elucidate how these socio-technical visions come with particular technological and societal choices. A summary table can be found at the end of this section (see Table 1). After this overview, a concluding discussion reflects on these visions and explores what this implies for shaping a large-scale research initiative.

3.1 Anticipating the direct conversion of solar light into fuels and chemicals

3.1.1 Actors

This vision is mainly articulated by biophysicists, biologists and chemists, which are supported by a few energy and chemical industrial players who view thermal catalysis as too energy consuming and thus search for alternatives. This group challenges thermal catalysis scientists and the energy, steel, cement and fertiliser industry, which rely on fossil fuels and feedstocks, advocate indirect conversion routes with high technology readiness levels and which are supported by the European Commission.

3.1.2 Framings

In this *framing,* what is central is a decentralised energy system that converts atmospheric carbon dioxide on-site and directly to fuels and chemicals by using solar light, implying a system that is disconnected from the established centralised energy infrastructure. This kind of system differs from the current one, with its indirect or multistep conversion routes, its dependence on energy imports, energy-intensive catalytic processes, reliance on expensive catalysts, knotty point source carbon capture from fossil-based processes and the high CAPEX associated with large-scale infrastructure and renewables. In contrast to '[thermal] catalysis scientists […] who are more or less the incumbents' and with the aim to learn from nature's photosynthesis, a scientist notes: 'nature is able to produce things from atmospheric CO2 in a decentral way […] energetically this is much more favourable and therefore cheaper' (Interview 4). It implies the creation of 'local closed loops' (Interview 9) and a 'small-scale economy' (Interview 9) by the on-site integration of, for example, sun, wind and carbon capture for the production of solar fuels and chemicals. Accordingly, this vision excludes the transport of energy carriers from areas with abundant renewable energy resources, while it is also observed that these practices are 'a form of neocolonialism, raising the question of whether this is desired' (Interview 4). However, certain industrial and transportation processes, particularly those in the

fields of ocean, air, and road transport, demand exceptionally concentrated energy sources. This poses a significant challenge for the stakeholders working towards the realization of synthetic fuels and chemicals in this vision.

3.1.3 Knowledge

Regarding *knowledge,* the actors involved in this vision note that 'the idea is to apply the discoveries in fundamental research into breakthrough technological solutions', while it is also important 'to move out of the ivory tower of fundamental research' (Interview 9). To do so, the technological solutions are assessed by industry because 'scientists fool themselves quite often but that is not possible in the industry, they have to deal with reality' (Interview 4) and by techno-economic, life cycle and thermodynamic analyses, which help 'to separate facts from values' (Interview 4). Additionally, this type of innovation can be accelerated by bringing together 'diverse groups, with different understandings and different visions of how their particular set of technologies can contribute to defossilisation' (Interview 9), surpassing thermal catalysis and including biology, physics, biophysics, energy ethics and social science.

3.1.4 Technologies and materials

In seeking to establish a more decentralised chemical and energy system without relying on fossil fuels, the vision's *technologies and materials* are closely associated to its framings. In contrast with energy-intensive processes such as point source carbon capture, electrolysis (hydrogen), Haber-Bosch (ammonia) and thermal cracking (hydrocarbons), this vision's actors propose a small-scale, lightweight and manufacturable system under real-life or mild conditions. It 'uses simple feedstock molecules that are widely available on our planet, namely water and atmospheric nitrogen and carbon dioxide' (Interview 9) as well as inexpensive catalysts or organisms for the direct and on-site conversion of solar light and wind into fuels and chemicals such as hydrogen, ammonia, methanol, olefins and kerosine. In this context, the 'off-grid energy generation installations' and 'local e-refineries' (Interview 9) are expected to be tailored to local needs and resources. As most of these technologies are at technology readiness levels between 2 and 4 and they produce 'high-value, low-volume products' (Interview 9), the proponents acknowledge that a hydrogen grid will also be required for specific industrial processes requiring highly concentrated energy.

3.1.5 Governance and institutions

Given these framings, knowledge and technologies and materials, prosumers[3], science, industry and legislation are important in *organising* the governance arrangement.

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[3] In this context, prosumers are citizens that produce as well as consume energy (e.g. with solar panels).

Regarding prosumers, the envisioned decentralised facilities allow energy communities to take control over running independent, off-grid systems that produce fuels and chemicals: 'When the sun shines, I could make my own green hydrogen. And when the sun is not shining at night, I could drive all my electricity at home, using the fuel cell and green hydrogen' (Interview 9). Science and industry relying on electrolysis can help in the governing of the upscaling of the technologies with low technological readiness levels. Additionally, legislation on carbon off-setting may lead the industry to support low technological readiness level technologies advocated by this vision, whereas it is also noted that the end products may also disrupt established industries.

3.2 Hand in hand: electrification and multistep conversions to synthetic fuels and chemicals

3.2.1 Actors

This vision emerges from companies in sectors such as the energy-intensive industry, aviation and maritime sector and from chemical engineers focussed on thermodynamic processes and life cycle analysis. They propose CCS and CCU, including multistep conversion routes to synthetic fuels and chemicals, as transitions technologies that go hand in hand with electrification. They oppose a diverse group of other actors such as those of the direct conversion routes, players advocating for CCS and CCU as permanent solutions or, otherwise, as delaying tactics, and actors who present green hydrogen and electrification (including gas transmission system operators) as exclusive solutions.

3.2.2 Framing

The *framing* of the actors cohering around this vision emerge from the observation that energy demand will grow over the next decades. To meet this demand, this vision proposes to indirectly convert (renewable) energy into synthetic fuels and chemicals by optimising current industrial processes such as point source capture, electrolysis, Fischer-Tropsch and Haber-Bosch. These processes, which have higher technological readiness levels than the direct conversion routes of the first vision, can be implemented in the EU and in areas with abundant renewable energy resources. Along these lines, the vision problematises renewable electricity and green hydrogen, which are subject to intermittency and develop slowly because of high investment needs, limited land availability, scarce raw materials and the absence of value chains, grids and storage space. As 'PV and wind are not always available' (Interview 10) and 'the green electrons [of REPowerEU] will not be here by 2030' (Interview 14), 'there simply is no alternative, there is no way of producing hydrogen with electricity' (Interview 6). Hence, for this vision, the development of high technological readiness processes goes hand in hand with, and is thus as important as, electrification. Nonetheless, most of the actors who relate to this vision frame CCS and CCU as 'transition technologies' as they may cause 'lock-ins'. An

expert from a petrochemical company says, 'capturing and storing our carbon dioxide allows us to continue the business as usual in our plants, so it will be a temporary solution' (Interview 14), while an energy company representative holds 'there's a risk that people and companies are going to use CCU and CCS to actually not change anything and continue fossil fuels use. That's what I call a lock-in' (Interview 13).

3.2.3   Knowledge

In terms of *knowledge*, this vision views science as having no direct connection to decision-making; there is a frontier between science and policy. It implies that scientific results are available to policy-makers, who can then develop rational policies based on these results. The actors refer to 'scientifically sound solutions' (Interview 10), the 'need for a consistent scientific assessment of these technologies' (Interview 6), and the role of an energy company's 'science council to tell [the company's board] what science says' (Interview 13). Such types of knowledge emerge from life cycle assessments, mass balances, carbon accounting and merit order rankings (i.e. economically optimising energy supply using the lowest marginal costs). Engineering research on the aforementioned technologies is important, but these scientists do not carry the responsibility to reflect on the embedding of their technologies in broader societal frameworks. Regarding social sciences, one interviewee adds that the energy transition's success also depends on understanding what society thinks. Another expert states that he works with 'science, and not the chattering sciences' (Interview 10). He acknowledges the importance of societal support, but stresses that this requires 'objective information', for which the views of (applied) scientists are crucial.

3.2.4   Technologies and materials

Technologies with high technological readiness levels are part of this vision's *technologies and materials*, with experts observing that 'the challenge is not technological. There are few gains to be made in terms of efficiency, but the main bottleneck is the business model' (Interview 13), while another expert says 'technologically, we think it's all possible' (Interview 10). The vision then attaches importance to the further development of different technologies such as carbon dioxide capture from point sources of the petrochemical, steel and cement industries, which can be used in innovative ways when these industries are integrated; equipping existing steam reformers, currently producing grey hydrogen, with carbon capture technologies as a transition technology from blue to green hydrogen; increasing the flexibility of electrolysers and industrial processes (e.g. steam-cracking) to account for changing energy prices and supply; and importing, from areas with abundant renewable energy resources, semi-finished products (e.g. sponge iron from direct reduction iron plants) and energy carriers and chemicals (e.g. methanol, methane and ammonia), although the carbon source of the imported carbon-based products is to be determined. Chemicals such as synthetic methanol can be used in the

chemical industry, while the fuels can be used in hard-to-abate sectors such as steel and cement, as well as in aviation and maritime. The use in cars and gas grids is however excluded.

3.2.5   Governance and institutions

Regarding the *governance and institutions*, the actors involved currently miss a consistent, long-term policy framework from the EU. Specifically and somewhat ambiguously – because the vision views synthetic fuels going hand in hand with electrification – these actors are currently not opting for a policy push to electrification, green hydrogen and, for example, direct reduction iron plants. However, a policy framework comprising subsidies and/or carbon penalties would accelerate the realisation of this vision. An expert from the petrochemical industry says that 'the development of rules could make these technologies affordable, which currently is the big dilemma' (Interview 14), while another expert says that 'a regulatory framework of policymakers could also keep certain industries in the EU' (Interview 13).

3.3   Being agnostic to the technology to reach shared carbon emission reduction goals

3.3.1   Actors

This vision is agnostic or neutral to the technologies to be used to reach shared carbon emission reduction goals. In particular energy technology companies adhere to this neutral vision to the technologies required because they sell the whole set of technologies, they try to keep all options and refuse to prioritise a particular industry. Similarly refusing to prioritise an industry, sector or technological approach, a couple of scientists and policymakers adhere to this vision. Additionally, as the vision is agnostic, it attempts to cover and involve multiple actors of the first and second vision.

3.3.2   Framing

Regarding the *framing* of this vision, the actors hold that technology is imperative to urgently reduce emissions and meet the increasing demand for affordable energy, while they are 'agnostic' to the type of technology to be used. A diversity of technological solutions helps to realise the shared goal of a shift away from fossil-based energy and feedstock in current industries, including direct and indirect conversion routes, green and blue hydrogen, biomass and electrification. An energy technology company expert states: 'It would not be smart to choose one technology already. The need for fuels and chemicals is huge and will continue to grow. Hence, it is important to support all these technologies and to see which one will win' (Interview 3). The winning technologies, in turn, will be based on the 'technologies they [companies] can really use in their commercial success' (Interview 3). Additionally, in the context of crafting a synthetic fuels and chemicals

community, a technologically oriented researcher adds countries, sectors and NGOs must be involved because:

> 'If we make a plan [for the European Commission], it might favour certain priorities. We must have all the tools in our hands to build that and, of course, the tools also imply opinions, propositions and so forth. If you miss something here [....] aren't you missing something for the bigger overarching challenge then?' (Interview 8)

Hence, the actors in this vision do not prefer a particular technology, taking an 'agnostic' approach to technology: 'we will need carbon-based fuels because hydrogen won't be all. Electrification won't be all [...] There is no silver bullet [...] The silver bullet will be a mix' (Interview 8). Notwithstanding this neutral approach, indirect conversion routes are considered important in the context of 'pressing time, so we need to start with technologies which we can scale, scale is the utmost need, bringing technologies from gigawatt to terawatt scale' (Interview 3).

3.3.3 Knowledge

Against the backdrop of this framing, the *knowledge* or forms of knowledge of this vision comprise developing technological solutions for industry and establishing a science-based consensus for policymakers. Concerning the development of technology for industry by scientists, an expert of an energy technology company holds that the main point is 'to understand what science and technology offer for new industrial solutions. [...] both to make money as to create environmental, social & governance (ESG) compliant companies' and thus 'the more or less simple job is to find overlap in these two fields' (Interview 3). In this context, 'scientists have to keep in mind that the technology they develop needs to be affordable in the end' (Interview 3). Regarding the establishment of a science-based consensus for policymakers, the actors of this vision hold that 'there is a frontier between politicians and scientists' (Interview 8), particularly using 'rational facts, rational analysis and life cycle analysis [...] scientists propose things to policymakers and politicians. They have to make the decision then' (Interview 8). Yet the actors of this vision also add that different actors, communities and societies may be involved in proposing the rational plan to the European Commission.

3.3.4 Technologies and materials

A plethora of technologies are considered in this vision's *technologies and materials*: 'the overall need for molecules and fuels is so large. There is space for various technologies and the technology that will best serve an individual need finally will win' (Interview 3), particularly each industrial player will 'reduce its costs by selecting the best technologies' (ibid.). The actors of this vision thus consider the direct and indirect conversion routes into synthetic fuels and chemicals, using all kinds of carbon sources, as well as (blue)

hydrogen and electrification. The applications include, inter alia, synthetic gas as a drop-in fuel, methane replacing coal as a bridging fuel and jet, maritime and sports cars fuels, applications in the steel, cement and petrochemical industries etc. In terms of the place of implementation and production, this vision is equally agnostic, noting 'it is basically a calculation of efficiency: is it better to have moderate good conditions for renewable production? [...] and save in transport? Or is it better to go to a place with the best renewable conditions and pay a bit more for the transport?' (Interview 3).

3.3.5   Governance and institutions

The vision's proposed governance arrangements build on the identified frontier between politicians and scientists: 'we as scientists propose solutions, we can't make decisions' (Interview 8). According to the actors in this vision, the decisions are then made by policymakers as well as markets. Specifically, policymakers decide on the best technological and science-based approach, for which they can then introduce incentives to reduce carbon dioxide emissions in the industry: 'some penalty on carbon dioxide emissions of industrial sectors will make them naturally follow the concept of carbon dioxide reduction' (Interview 3). Additionally, policymakers are expected to fund technologies with lower technological readiness levels such as direct air capture and direct conversion routes: 'if we really want to foster them, they really need to be funded by the government and the community' (Interview 3). In the end, the actors note, 'all relies on politicians and society' (Interview 8), although an expert adds 'we need to make people aware that we work on new technologies, we need to explain them the benefits' (Interview 3).

3.4   Prioritising renewable energy and electrification

3.4.1   Actors

Energy sector institutes and experts as well as European NGOs are the main actors contributing to this vision. They rally against a 'hydrogen hype' (Interview 11) and 'technological neutrality, which sows doubt about synthetic fuels and chemicals [...], which are in fact expensive, inefficient and pushing them is a delaying tactic of the industry' (Interview 15). Additionally, a few experts from petrochemical and energy companies of the previous visions note they wear multiple hats (e.g. as citizen, scientist and business representative) but internally, in their companies, defend this electrification vision. This vision's actors condemn multiple other actors who blow hot and cold about synthetic fuels and chemicals (i.e. they may use different, contradictory statements in different contexts): those 'who heat with natural gas and see hydrogen as a way to not having to change their entire production processes' (Interview 15), the gas industry, parts of the car industry, energy technology companies, eFuel Alliance, shipping and logistics companies, aviation industry and fossil fuel companies.

3.4.2 Framings

Regarding *framings*, by prioritising the direct use of renewable electricity and electrification, this vision distances itself from hydrogen as well as from direct and indirect conversion routes to synthetic fuels and chemicals. The actors observe that a shift to green electricity is not gaining traction and they thus question the rationality of using that scarce electricity to produce green hydrogen and, accordingly, synthetic fuels and chemicals. An energy expert worries about 'putting aside green electricity for green hydrogen's production, while the rest of the electricity mix continues to run on coal and gas' (Interview 11) and an NGO adds it is important to 'not take away renewable energy or electricity from other sectors that need it' (Interview 12). The actors involved in this vision continue to criticise synthetic fuels and chemicals, especially in cars, because of the low energy efficiency of producing them. On these grounds, the actors refute the imports of, for instance, green ammonia, as a hydrogen carrier, to the EU to then decompose it to hydrogen.

On top of this scarcity and low efficiency, this vision cautiously considers demand-side interventions and recycling. An expert from a petrochemical company defends, in principle, 'the electrification of the chemical industry [...] and maximising circularity with, for example, plastics recycling [...] Hence, circularity goes hand in hand with electrification' (Interview 14). When synthetic fuels and chemicals are considered (see below), an NGO adds that 'tracking where the carbon comes from and where the carbon goes is really crucial [...] not only during the product's lifetime but also at the end of the lifetime of the product' (Interview 12). However, in the context of demand-side interventions, an NGO adds 'we mainly work on CO2 standards because this is where the EU can intervene' (Interview 15), while another NGO notes:

> 'it is difficult, especially for cement and concrete, what kind of impact that could have on emissions [...] also because it is sometimes a very difficult social issue. Do you want to close a cement plant? And is that your decision to make as a climate activist? We focus on the production side because it is a more just approach, at least it's a simpler approach' (Interview 12).

In this context, finally, the actors in this vision are willing to consider the production and use of synthetic fuels and chemicals under specific conditions, which are captured by three overlapping questions. The first question to answer relates to the energy efficiency performance of synthetic fuels and chemicals: the use in cars is excluded, but so-called hard-to-abate sectors such as aviation, maritime and energy-intensive industries can be discussed (see below in the *technologies and materials* of this vision). Second, questions should be posed about the energy and carbon source: the use of additional renewable

energy and, in principle, biogenic and atmospheric carbon are preferred, although exceptions can be made for hard-to-abate industries in a transition phase. Finally, the question is what the final use of these fuels and chemicals is. Here, CCU that is close to permanent storage gets priority.

3.4.3   Knowledge

In terms of *knowledge* and along the lines of the framing of this vision, the actors mainly rely on economic and energy efficiency assessment frameworks that serve as science-based policy input. One energy sector researcher emphasises 'a kind of sound, optimal techno-economic overview […] from which the political debate can depart' (Interview 11), resembling the frontier between politicians and scientists of the third vision. Other experts speak of a 'robust assessment framework' (Interview 12) to include the three questions addressed in the framing of this vision, as well as using energy efficiency frameworks which can be used 'to make data-driven and informed decisions' (Interview 15). Additionally, the whole electricity system, in full detail, needs to be assessed because it is often assumed that renewable electricity is abundantly available. To the knowledge considered in this vision, one expert from an NGO adds 'wherever the taxpayer is chipping in, there needs to be a stakeholder involved that is representing the common good and that is representing not the interests of an industry but the interests of the people and the climate' (Interview 12). Notwithstanding the role of technology experts, this may be achieved, accordingly, by involving 'peer reviewed academics who really know what impact the technology would have on the climate […] civil society organisations that represent at least parts of society […] and an elected element, or at least a European institution'.

3.4.4   Technologies and materials

Given the emphasis on electrification and the three questions specifying the requirements for synthetic fuels and chemicals, this vision's *technologies and materials* for synthetic fuels and chemicals are well-specified. Synthetic fuels are not considered for injection in the gas grid, or for luxury purposes such as cruise ships and road transport, with an NGO stating, 'it's the physics stupid, it makes no sense to do something [road transport] at 22% efficiency if you can do it at 80% using battery electric [vehicles]' (Interview 15). In turn, in a few hard-to-abate sectors synthetic fuels are considered. For example, 'for [international] aviation, you just have one technology, the jet engine, so you don't have many options to decarbonise it' (Interview 15). Likewise, maritime applications are included, although less straightforwardly because these are more diverse in terms of fuels (e.g. fuel cell, e-methanol and e-ammonia) and transport modes (e.g. ferries, riverboats and ocean transport). Only when the more efficient option of electrification is impossible, synthetic fuels and chemicals play a role in the steel, cement, chemical and petrochemical sectors. Yet, these fuels and chemicals can only be produced using, in

essence, biogenic or atmospheric carbon, although point sources under EU ETS are relevant in a so-called transition phase. An NGO proposes 'a robust assessment framework that could then filter out the best CCU projects, [...] encouraging a form of CO2 utilisation that is closer to permanent storage' (Interview 12). Finally, if the import of synthetic fuels and chemicals is deemed necessary, an NGO adds that, particularly for the Global South, 'the import scheme should be used as a lever to constitute something local, renewable electricity, a grid, a network and jobs' (Interview 15).

3.4.5 Governance and institutions

Along the lines of the vision associated with indirect conversion routes, albeit with other goals, the *governance* of this vision emphasises a consistent, long-term policy framework from the EU in the direction of renewables and electrification instead of green hydrogen. In the context of reducing emissions using synthetic fuels and chemicals in hard-to-abate sectors, such a framework 'holds every industry to the same standard [...] making sure they all have the incentives and financing that they need for lift-off' (Interview 12), which 'potentially is gaining ground under initiatives such as the Renewable Energy Directive III, Hydrogen Bank and Carbon Contracts for Difference' (Interview 15). In line with the vision's *knowledge,* the actors rely on robust assessment frameworks and energy efficiency analyses to make science-based and data-driven policy decisions about this framework. As the vision's *knowledge* consider a broader set of stakeholders, an NGO adds 'keeping that dialogue between these different stakeholders is really important [...] to make sure the plans that are made are viable from a climatic, societal, environmental and economic point of view'. (Interview 12).

3.5 Building a just and electrified energy future

3.5.1 Actors

The core actors of this vision are NGOs and civil society actors such as labour unions who advocate for a just and electrified energy future, which is an objective that resembles the fourth vision although a focus on social justice is added here. Just like in the fourth vision above, the actors under this fifth vision oppose 'the powerful hydrogen lobby, which is, in fact, the natural gas industry' (Interview 17), as well as the 'technological neutrality perspective' reproduced by the third vision and the 'narrow' focus on solar or synthetic fuels and chemicals of the first and second vision.

3.5.2 Framings

This vision's *framings* relate to synthetic fuels and chemicals head for a just and green energy future. As in the fourth vision, major concerns for the actors of this vision are the scarcity of renewable energy and the low efficiencies of synthetic fuels and chemicals, making them expensive. A labour representative shares, for example, the position that 'the efficiency of the battery-electric vehicle is much higher than the one on e-fuels or

hydrogen' (Interview 16), 'cost efficiency scenarios of hydrogen need to be compared to, for instance, electrification and heat pumps' (Interview 17) and the power used for synthetic fuels and chemicals production should be additional renewable energy.

Challenging the 'technological neutrality' framing of the industry, the European Commission and the third vision identified here, this vision defends 'conditional technological neutrality' because:

> 'many of these technologies are not neutral in terms of impact on society. This is true in Europe and globally speaking. To us, it is absolutely clear that technology neutrality should not be a blank cheque for the industry to do what they want and to choose for low-cost options' (Interview 16).

Another NGO continues, 'technological neutrality, that doesn't exist as every step taken moves in the direction of a particular technology' (Interview 17). In this context, the actors of this vision worry about innovation at the expense of human rights, the impact on employment, social justice and, in essence, about 'who does the efforts, who pays the bill, who gets support schemes [...] and if it is always the same groups, you will end up with a lot of tensions and conflicts' (Interview 16).

In addition to the concerns over scarcity, low-efficiencies and the use of technological neutrality as a frame, the actors note that 'technical arguments are frequently mobilised by the industry to narrow the focus of the discussion to illustrate synthetic fuels are good [...] and you actually need someone to open the discussion again' (Interview 17). By doing so, many knotty issues emerge such as the non-existence of abundantly available renewable energy, the materials needed for a shift to synthetic fuels and chemicals and the role of circular economy strategies therein, the impacts on societies across the globe and the role of flying less in the context of sustainable aviation fuels. Furthermore, they note that there will be trade-offs, raising difficult questions about who uses synthetic fuels and chemicals for what and for whom? Do societies need more (synthetic) ammonia? Are investments in synthetic fuels for yachts, cruise ships and sports cars essential in comparison to investments in hospitals and schools? Generally, the actors of this vision thus note that 'the innovation potential is too often used as a pretext for not opening a discussion on our needs, our way of life and our behaviour' (Interview 16) and ask 'what is innovation and what is its objective?' (Interview 17).

3.5.3 Knowledge

Two main types of intertwined *knowledge* are relevant in this vision, namely one on climate and quantitative assessments in the context of planetary boundaries and another

one that facilitates opening the focus of the synthetic fuels and chemicals discussion. Regarding the former, a a labour union actor's personal opinion is:

> 'we need to design industrial policy and technology development within planetary boundaries. Too often the mistake is to believe that we can [...] strike the right balance between protecting the environment and defending industry. No, I think this is the wrong way to approach the debate. Climate science is there [...] within the frame of what is feasible according to that science, we have to discuss the kind of economic policy, industrial policy, the kind of technology development we want' (Interview 16).

In this context, the actors ask for quantitative assessments of independent scientists across all sectors and applications (e.g. cars, aviation, maritime, steel and chemical) of, for example, hydrogen and synthetic fuels supply and demand. Such an assessment not only teases out various tensions but also needs to be complemented with a needs assessment, uncovering hidden assumptions about, for example, the growth scenarios in the aviation industry.

To challenge those hidden assumptions, the actors involved attach importance to the roles of process facilitators and social science and humanities scholars. Specifically, they may open the focus of the synthetic fuels and chemicals discussion beyond narrow industrial and technical perspectives to include more fundamental discussions. Here 'breaking a bit the epistemological silos' (Interview 16) is deemed important, particularly the 'opening of spaces where we can discuss [...] on the ground, discuss with people, involve them at the early stages of the decision-making process, listen to their concerns, proposals and suggestions' (Interview 16). These 'people' include industry, policymakers, local communities and civil society from the West as well as the Global South. Another NGO adds it is about 'merging' several arguments and perspectives and their hidden assumptions in 'a difficult discussion that, in the end, influences what innovation will look like' (Interview 17).

3.5.4 Technologies and materials

This vision's *technologies and materials* result from the observed scarcity of renewable energy, the low efficiency of synthetic fuels, an interest in reindustrialising the EU, as well as opening the focus of the discussion. Given the scarcity and low efficiency, renewable energy and electrification technologies are prioritised instead of synthetic fuels and chemicals. Specifically, an NGO expert states: 'electrification just works, you cannot argue against it anymore, it is present and will only grow in the future' (Interview 17). The vision thus excludes synthetic fuels for injection in the gas grid, domestic heating, cars and even a big part of energy-intensive industrial processes, which may be electrified. As

mentioned, it holds that distinguishing essential and non-essential uses of sustainable fuels and chemicals is crucial.

Furthermore, the actors argue against imports of synthetic fuels to avoid 'a kind of neo-green colonialism, where you basically fulfil your own agenda without paying attention to the interests and the rights of the local populations' (Interview 16). Simultaneously, they promote the re-industrialisation of the EU by bringing back a series of supply chains and manufacturing activities, which 'could be a win-win-win for companies, employees and the climate' (Interview 17). Notwithstanding these arguments, the *framing* and *knowledge* of the vision emphasise the opening up the discussion on synthetic fuels and chemicals to include contextualised (see *governance and institutions*) and fundamental questions about what innovation and technology are and whose goals these serve, also including discussions about using synthetic fuels and chemicals and CCU in sectors such as industry, aviation and maritime.

3.5.5   Governance and institutions

Regarding the *governance and institutions*, the actors of this vision highlight that the governance of technology and, in essence, the energy transition requires an approach that can be labelled as anticipatory, multidimensional and embedded in local contexts. The approach emerges from the observation that there are differences across, countries, regions, sectors and communities, with the actors noting 'there is no one size fits all in those discussions' (Interview 16). When considering, amongst other factors, the potential of solar PV, wind and hydro, the current electricity mix and industries, landlocked regions and socio-economic and industrial relations, it becomes clear that different solutions are needed in, for instance, North-West Europe, Central and Eastern Europe and the Global South.

These actors mention 'local ownership to discuss those things, the different options, their consequences', which requires a 'multi-dimensional ex-ante assessment' (Interview 16) or a 'quadruple helix model' (Interview 17), involving government, academia, industry and civil society actors. Such an approach may help to address questions such as 'what kind of industry do you want to give shape' (Interview 17), potentially leading to the development of contextualised, multidimensional and anticipatory transformation plans for the next decades. Nevertheless, the actors behind this vision caution against industries and policymakers who have 'a tendency to create a sense of urgency, which might lead to bypass a series of democratic and environmental requirements' (Interview 16) in order to accelerate innovation.

Table 1: Five socio-technical visions

	Vision 1 - Anticipating the direct conversion of solar light into fuels and chemicals	**Vision 2** - Hand in hand: electrification and multistep conversions to synthetic fuels and chemicals	**Vision 3** - Being agnostic to the technology to reach shared carbon emission reduction goals	**Vision 4** - Prioritising renewable energy and electrification	**Vision 5** - Building a just and electrified energy future
Supporting actors	Biophysicists, biologists and chemists; energy and chemical companies	Energy-intensive, aviation and maritime sectors; chemical engineers	Energy technology companies; actors of vision 1 and 2	Energy sector institutes, environmental NGOs, scientists associated with this vision	NGOs focussed on the environment; labour unions; scientists associated with this vision
Actors challenged	Thermal catalysis scientists and industrial companies relying on indirect conversion routes	Direct conversion vision, advocates of CCS and CCU as permanent solutions, green hydrogen and electrification diehards		Hydrogen hypers, technological neutrality actors, gas industry, parts of the car industry, energy technology companies, fossil fuel companies, aviation industry …	Hydrogen lobby, natural gas industry and proponents of vision 1, 2 and 3
Framings	• Multiple limitations current energy and industrial system • Learn from photosynthesis, using atmospheric CO_2	• Energy demand increases • Limitations renewables • So, optimise current industrial processes,	• Need for fuels and chemicals is huge • Agnostic to type of technology used to meet needs	• Scarcity renewable energy • Consider demand-side • Synthetic fuels and chemicals: efficiency?	• Scarcity renewable energy and low efficiency synthetic fuels and chemicals • Conditional technological neutrality;

	• Local closed loops instead of neocolonial imports	multistep conversions and imports • Transition technologies: CCS, CCU and blue H	• Favours higher TRL, indirect routes in the context of urgency	Energy and carbon source? Application?	no innovation at expense of justice • Knotty issues and questions: what is the objective of innovation?
Knowledge	• Fundamental research on technological solutions, leaving 'ivory tower' • Solutions assessed by industry and techno-economic and LCA analyses • Diverse understandings	• Scientifically sound solutions • Rational policies based on science • LCA's, mass balances, carbon accounting	• Science-based consensus for policymakers (i.e. frontier) • Rational facts and analysis • Develop affordable technological solutions for industry	• Economic and energy efficiency assessment as science-based policy input • Asses whole electricity system; renewables not abundantly available • Stakeholder involvement if 'taxpayer is chipping in'	• Quantitative assessment in context of planetary boundaries • Challenge hidden assumptions by organising discussion
Technologies and materials	• Lightweight, manufacturable system, works under mild conditions • On-site, direct conversion of solar light to fuels and chemicals • Local e-refineries	• Challenge is not technological • Multistep conversions, point source carbon capture, blue hydrogen, flexibility industrial processes	• Depends on policymakers • Depends on how an industry wants to reduce its costs • Based on a calculation of efficiency	• Renewables and electrification • Synthetic fuels: not in gas grid, not in cars, no luxury • Biogenic or atmospheric carbon, although transition period needed • If imported, contribute to local objectives	• Renewables and electrification • Imports: neo-colonialism • Re-industrialising EU • Discussion on contextualising synthetic fuels and chemicals

| **Governance and institutions** | • Prosumers using independent, off-grid system
• Help from indirect conversion actors on upscaling technology
• Legislation to foster industry's support | • Need consistent, long-term policy framework
• Rules and subsidies to make technologies affordable
• Carbon penalties | • Policymakers decide, then introduce incentives for markets/industry
• Carbon penalties
• Funding for lower TRL technologies
• Explain benefits to society | • Need consistent, long-term policy framework, including incentives and financing
• Science-based policy decisions
• Dialogue between stakeholders | • Governance approach that is anticipatory, multidimensional and embedded in local contexts
• Quadruple helix model
• Democratic requirements over sense of urgency |

4 Concluding discussion

The objective of this report is to identify socio-technical, cross-cutting challenges related to the development and deployment of sustainable fuels and chemicals. The approach first identified the different interpretations and visions that exist about sustainable fuels and chemicals, their role and their implications. What do we learn from this? The results are discussed in two steps. First, the main cross-cutting, societal issues that surface over the five visions are addressed. Second, the implications for the SUNER-C project and its possible development into a large-scale research initiative are considered.

4.1 An overview of important socio-technical cross-cutting challenges

It was already stated in the introduction: technology is never 'just' technical. It is part of a broader socio-technical system and future expectations are also socio-technical. This means concretely that behind the visions, there exist different views of society and its economic and political organisation. The visions imply for example different choices in terms of the (future) roles and responsibilities of government, industry, science, societal stakeholders or consumers. The visions also lead to different choices in the selection of research priorities and directions, R&D and infrastructure investments, strategy-development with partners, commissioning research, lobbying, legislative proposals, press releases and so forth. We illustrate these implications through a brief discussion of the main cross-cutting, societal issues across the four categories of the analytical tool (i.e. *framing*, *knowledge*, *technologies and materials* and *governance and institutions*) in the five socio-technical visions, namely:

- Vision 1 – Anticipating the direct conversion of solar light into fuels and chemicals
- Vision 2 – Hand in hand: electrification and multistep conversions to synthetic fuels and chemicals
- Vision 3 – Being agnostic to the technology to reach shared carbon emission reduction goals
- Vision 4 – Prioritising renewable energy and electrification
- Vision 5 – Building a just and electrified energy future

4.1.1 Cross-cutting challenges derived from 'framings'

For the component of 'framing' – or defining problems and their respective solutions – a range of cross-cutting issues emerge when glancing over the five identified visions. For some challenges there seems to be convergence around the framing, i.e. often the challenge may be identical, but the framing, in particular of solutions for the challenge, is quite different. What are the Important cross-cutting challenges that have been identified under this component?

- **climate change**: this is a common driver behind all visions and is treated as a self-evident starting point.

- **energy security**: also present in all visions, but its meaning is in general not further defined.
- **the role of imports**: some visions are concerned about imports and green neocolonialism (cf. vision 1 & 5), arguing for more local and small-scale solutions and technologies (cf. vision 1) or renewable energy and direct electrification in the EU (cf. vision 4). Others consider imports a necessity (cf. vision 2).
- **affordability of the transition**: all visions see this as a challenge, but the implied actors can be quite different, with on the one end industrial sectors and the costs and benefits they expect from a transition, and on the other end the cost and benefits for workers and citizens. In particular in the latter case, the framing relates to questions of distribution and just transition (cf. vision 5).
- **the (growth in) demand for energy, fuels and chemicals**: some visions treat economic growth and growth in demand for energy and chemicals as a given and project a supply that follows demand (cf. vision 2 and 3). Other visions see a necessity for demand-side interventions and recycling to keep demand under control (cf. vision 4 and 5).
- **the source of (renewable) energy and carbon**: visions differ in what are acceptable sources of (renewable) energy and carbon used for sustainable fuels and chemicals, over what periods of time. With regard to energy, to some, the current industrial and energy system faces limitations, requiring less energy-intensive technologies (cf. vision 1) or optimisation of the current technologies (vision 2). What is more, some only want additional renewable energy to be used for sustainable fuels and chemicals production (cf. vision 4). Concerning carbon, atmospheric and biogenic carbon may play a role (cf. vision 1 & 4). Other visions focus on point sources and blue hydrogen (cf. vision 2), while still others note local contexts matter (cf. vision 5).
- **the application of sustainable fuels and chemicals** (for more details see under 'technologies and materials'): some visions have no explicit view on the acceptability of purposes and use-phase of sustainable fuels and chemicals, while others explicitly question for which end-products fuels and chemicals are acceptable or not, and also want innovation to adhere to certain principles (such as human rights and social justice) (cf. vision 5).

As said above, the way the different visions treat these cross-cutting challenges is not neutral. The answer to any of these challenges has implications for e.g. R&D investments, infrastructure development, legislation, value chains, and societal relations that all give shape to the future energy and industrial system. In any case, the analysis of the 'framings' component shows that apart from technological questions, also other **questions** have to be answered, such as:
- How fast can/should technologies and other measures develop and be deployed, and do they live up to the urgency of climate mitigation?
- As renewable energy is not abundantly available, what exactly is the source of (renewable) energy and carbon used for sustainable fuels and chemicals, over what periods of time?

- How do direct electrification and demand-side interventions relate to sustainable fuels and chemicals?
- How are the costs and benefits of this transition distributed over sectors and populations?
- Where will sustainable fuels and chemicals be produced, and at the advantage or expense of whom?
- Which end uses are acceptable and which are not?

4.1.2 Cross-cutting challenges derived from 'knowledge'

Within the component of 'knowledge' or the knowledge inputs and outputs, the following cross-cutting issues emerge. As with the component of 'framing', there is considerable convergence for some challenges, while for others there are clearly divergent views.

- **The role of science**: most visions attach to a greater or lesser extent importance to fundamental research, technological solutions and assessments of those technologies by means of techno-economic, lifecycle and mass balance analyses. On this basis, science-based and rational decisions can be made by policymakers and/or markets, industry and companies (cf. Vision 1-4) or within the framework of planetary boundaries (cf. Vision 5). The role of social science is sometimes restricted to creating social acceptance (vision 2), but in other cases deemed important for clarifying underlying assumptions and opening more fundamental discussions (vision 5).
- **The role of societal knowledge and stakeholders**: visions differ in the importance they attach to the expert knowledge from diverse societal groups. Some value stakeholder involvement (cf. vision 1, 4, 5) and see the need for a quadruple helix model to open the focus of the highly technical sustainable fuels and chemicals debate towards new knowledge on, for instance, the role of sustainable fuels and chemicals in our societies. Other visions refer to a triple helix model (see also below 4.1.4)

Again, it is obvious that the way these cross-cutting challenges are treated, leads to different research priorities and investments, to a different valuation of types of knowledge and, in essence, to different types of economies, societies and industries. In any case, the analysis of the 'knowledge' component shows that apart from technological questions, also other **questions** have to be answered, such as:

- What knowledge is deemed relevant for innovation in sustainable fuels and chemicals, why, according to and at the expense or benefit of whom?
- What knowledge or perspectives are considered and are there openings for countervailing views? Who and what is (not) taken into account?

4.1.3   Cross-cutting challenges derived from 'technologies and materials'

For the component 'technologies and materials' or technologies and material commitments, the following cross-cutting aspects surface.

- **Choice of central technologies** for the development of sustainable fuels and chemicals: some visions and the associated actors propose lightweight and manufacturable technologies operating under mild conditions, which can be used on-site and locally to convert solar light into fuels and chemicals (cf. Vision 1). Here a decentralised energy and industrial system is anticipated, whereas other actors advocate for optimising the current system through multistep conversion routes that rely on more established processes such as point source capture, electrolysis, Fischer-Tropsch and Haber-Bosch (cf. Vision 2). Still others note it is crucial to invest in and develop renewable energy and direct electrification (cf. Vison 4 and 5).
- **End-use or application of sustainable fuels and chemicals** (see also under 'framings'): Some actors consider nearly every type of application, including for energy-intensive industries; all sorts of chemicals; e-methane as bridging fuel; and drop-in fuels for sports cars, maritime transport and aviation (cf. Vision 2 and 3). Others note the application needs to be tailored to local needs and resources (cf. Vision 1). Still others note sustainable fuels and chemicals will be scarce because of the limited availability of renewable energy and feedstock, leading them to introduce notions of efficient applications, essential and non-essential applications and to the exclusion of luxury purposes (cf. Vision 4 and 5).

Once more, the way the different visions treat these cross-cutting challenges is not neutral. The answer to any of these challenges has implications for, amongst other things, different R&D agendas, investments, future infrastructure, value chains and societies. In any case, the analysis of the 'technologies and materials' component shows that apart from technological questions, also other **questions** have to be answered, such as:

- Should sustainable fuels and chemicals be produced in a more centralised or decentralised system?
- Who wins and who loses in these different systems?
- Where will this system be located?
- How does renewable energy and electrification lead to different infrastructure?
- Concerning applications, questions can be raised about who, particularly what sectors and companies, will acquire or receive sustainable fuels and chemicals, why them and for what purposes?
- If these fuels and chemicals are scarce, is distinguishing essential and non-essential applications required?
- Who (markets, governments, consumers, industry, civil society, local communities etc.) decides on essential and non-essential uses?

4.1.4 Cross-cutting challenges derived from 'governance and institutions'

Under the component of 'governance and institutions' or governance and social organisations, the following cross-cutting challenges emerge.

- **The policy framework**: most visions and the associated actors demand a policy framework based on science. The framework then consists of science-based rules, subsidies for particular technologies and carbon penalties, which help to accelerate the uptake of the technologies of the particular vision (cf. Vision 1-4). The preferred mix between regulation, markets and voluntary measures cannot be decided from the analysis for this report, but is also under debate in the scientific literature.
- **The innovation model:** in vision 2 and 3 a triple helix model is proposed, in which the governance of innovation happens on concertation between government, industry and science. Other visions favour a form of a quadruple helix model, since they propose to involve prosumers in taking control over decentralised systems (vision 1), broader stakeholder involvement if public money is used (Vision 4), or a quadruple helix model as a general governance approach (cf. Vision 5).

The different technology choices come with different implications for governance and a different mix of instruments (regulation, markets, voluntary measures), and will consequently lead to other political struggles. In any case, the analysis of the 'governance and institutions' component shows that apart from technological questions, also other **questions** have to be answered, such as:

- How do particular governance arrangements enable the development of specific visions of sustainable fuels and chemicals?
- Who gets a seat at the decision-making table, why and to what ends?
- Who benefits from a certain governance arrangement and its 'outputs', and who does not?
- Whose perspective and knowledge is recognised in the governance arrangement?

4.2 Implications for the SUNER-C project and a possible follow-up in an LSRI

As said in the introduction, scientific and technological innovations are always influenced by and entangled with societal, economic, political and cultural evolutions and demands. The analysis above has proven this once more. If this idea of co-production is taken seriously, it follows that the trade-offs between these societal implications that are manifested in technology decisions, should not be made by technology-developing research and industry alone, but should be made in open dialogue and with input from policy-makers, societal stakeholders like unions and NGOs, and a broad pallet of knowledge. There are at least two implications for the SUNER-C project.

4.2.1 Implications for the current project

The analysis showed, first, that the 'technological approaches' of SUNER-C are, in fact, socio-technical visions in which societal choices are continuously made. Second, that the technological visions diverge widely and that these reflect and imply different underlying, fundamental societal choices. Third, due to the normativity and performativity of visions, a debate about future technologies, requires the involvement of societal stakeholders and different disciplinary 'knowledge holders'. These findings should form the basis for a deeper debate about sustainable fuels and chemicals in the current SUNER-C community. It seems necessary to create spaces for acknowledging and discussing the mentioned cross-cutting issues, and investigating how they can be translated into the different work packages.

To give one example. Work Package 3 has the development of a "technological roadmap" as an objective. Several working groups will discuss the further development of technological pathways such as electrochemical conversion, photosynthetic devices, biological conversion, solar-thermal conversion, sustainable CO_2 capture, and computational materials sciences, all with the goal of contributing to the development of sustainable fuels and chemicals. All of these technological pathways will be confronted with the kind of socio-technical cross-cutting challenges identified above, and all of them will be influenced by them. Creating space for debate during the working groups with societal stakeholders and different disciplinary 'knowledge holders' to identify challenges and solutions would then be a logical step.

What can be helpful here, is the proposal for a **conversation tool** that we have been experimenting with in view of Task 6.3 (which is in fact a task for later in the SUNER-C project, starting in month 25). This task aims at the development of a strategy for the integration of cross-cutting issues in a possible future large-scale research initiative (LSRI). The tool consists of a set of questions and some guidance for use. While in a first version, the questions were based on guidelines from technology assessment, we have replaced them here with the questions that derive from the cross-cutting challenges identified above. This is again a preliminary version and will be further developed later in the project for Deliverable 6.3. Possibly, both versions will be integrated. See the frame below for explanation on using the tool and the tool itself with the questions.

Preliminary version of a 'Conversation Tool'

This tool aims to guide and inform conversations about societal considerations in SUNER-C and initiate reflection and conversation when for example working on the vision, the roadmap, the connection with industry and other stakeholders, or the development of a future LSRI. This document provides basic guidelines on how to use the tool and why it is important to include such conversations at an early stage of technology development.

Why use the Conversation Tool?

Technological developments come with a number of societal questions that need to be discussed in view of ensuring that research and innovation are being executed in a responsible manner. The tool serves to raise a number of societal issues, initiate a conversation and determine to what extent it is desirable and essential to take these considerations into account when further developing and implementing the technology at hand. By doing so it aims to reduce or avoid human and social costs of learning how to handle technology in society by including societal considerations in the development process, as opposed to learning through trial and error.

It is important to start thinking early about potential positive and negative effects of technological change. The insights derived from such an assessment (or conversation) can then feed back into choices and decisions about technology development and deployment leading to a co-production of technology and society.

How to use the conversation tool?

At a first stage the conversation tool is meant to be used within the SUNER-C/SUNERGY-community. For example, when developing the vision (WP1) or road map (WP3) where it is essential to include societal considerations. It is therefore strongly recommended to dedicate time in your working process, **reserve a session in your working group**, and embark on a discussion with your working group members by means of the conversation tool. Appoint a **moderator** who prepares the conversation and a **minute taker** who collects the working group members' input. The conversation tool serves as a guidance for the dialogue session and can be **used as a strict guidance or as a general framework** for initiating an organically evolving discussion on the different societal issues relevant for the topic.

Having such a dialogue allows you to gain broader insights in the topic and collect a wide range of viewpoints on the related societal aspects. These conversations help to better analyse and develop the work at hand with inclusion of potential positive and negative consequences requiring anticipation. The collected input from these dialogue sessions is expected to **feed into and be reflected in the project deliverables**.

In this way, it allows for the **integration of alternative sources of views to enrich reflection** and it enhances the knowledge about the technology, including the **framework of values used by stakeholders initiating support or resistance for the technology**. It thereby supports a well-informed decision making process required for a sustainable development and implementation of new technologies

The Conversation Tool

The tool consists of a set of questions to start a conversation about the societal implications of the technologies. The questions are ordered in four categories.

1. **framing of the technology**: relates to the problems the technology wants to solve, different solutions, motivations and challenges. Possible questions for conversation:
   - As renewable energy is not abundantly available, what exactly is the source of (renewable) energy and carbon used for sustainable fuels and chemicals, over what periods of time?
   - How do direct electrification and demand-side interventions relate to sustainable fuels and chemicals?
   - How are the costs and benefits of this transition distributed over sectors and populations?
   - Where will sustainable fuels and chemicals be produced, and at the advantage or expense of whom?
   - Which end uses are acceptable and which are not?

2. **knowledge**: relates to the knowledge inputs that are necessary and the expected knowledge outputs that result from socio-technical futures. Knowledge can derive from scientific research, but can also be based on experience or observation, or can be tacit; it can be qualitative or quantitative. Possible questions for conversation:
   - what knowledge is deemed relevant for innovation in sustainable fuels and chemicals, why, according to and at the expense or benefit of whom?
   - What knowledge or perspectives are considered and are there openings for countervailing views? Who and what is (not) taken into account?

3. **technologies and materials**: refers to the technological and material choices that are necessary. Possible questions for conversation:
   - should sustainable fuels and chemicals be produced in a more centralised or decentralised system?
   - Who wins and who loses in such a system?
   - Where will this system be located?
   - How does renewable energy and electrification lead to different infrastructure?
   - Concerning applications, questions can be raised about who, particularly what sectors and companies, will acquire or receive sustainable fuels and chemicals, why them and for what purposes?
   - If these fuels and chemicals are scarce, is distinguishing essential and non-essential applications required?
   - Who (markets, governments, consumers, industry, civil society, local communities etc.) decides on essential and non-essential uses?

4. **governance and institutions**: relates to the methods of social and political organization, the explicit and implicit rules that guide this organization, as well as to the utilization of various regulatory, economic, or voluntary mechanisms in shaping the future
   - How do particular governance arrangements enable the development of specific visions of sustainable fuels and chemicals?
   - Who gets a seat at the decision-making table, why and to what ends?
   - Who benefits from a certain governance arrangement and its 'outputs', and who does not?
   - Whose perspective and knowledge is recognised in the governance arrangement?

4.2.2   Implications for a possible follow-up in an LSRI

One of the ambitions of SUNER-C is to develop towards an LSRI for sustainable fuels and chemicals. The analysis above shows that in that case it is highly recommendable to ensure a better integration of societal questions and of societal stakeholders. This will be further taken up in task 6.2 ('Stakeholder dialogue on implications for transition pathways') and task 6.3 ('development of a strategy for cross-cutting issues') of WP6. This can, however, emphatically, not be a job for WP6 alone. Without cross-cutting challenges entering in the core of other WP's, they will not suddenly surface in a proposal for an LSRI.

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Appendix

Interviews and in-depth conversations

#	Date	Info	Type
1	18/10/2022	Civil society: environment	In-depth conversation on societal and technical issues in SUNER-C
2	20/10/2022	Researcher: chemical engineer	In-depth conversation on societal and technical issues in SUNER-C
3	17/11/2022	Industry: energy technology	Interview
4	18/11/2022	Researcher: chemistry	Interview
5	21/11/2022	Civil society: environment	In-depth conversation on green steel
6	22/11/2022	Researcher: policy	Interview
7	23/11/2022	Researcher: social scientist	In-depth conversation on societal and technical issues in SUNER-C
8	24/11/2022	Researcher: energy technology	Interview
9	8/12/2022	Researcher: solar fuels	Interview
10	9/12/2022	Industry: steel	Interview
11	19/12/2022	Researcher: energy sector	Interview
12	27/3/2023	Civil society: environment	Interview
13	30/3/2023	Industry: energy	Interview
14	11/4/2023	Industry: oil & gas	Interview
15	20/4/2023	Civil society: environment	Interview
16	20/4/2023	Civil society: labour union	Interview
17	23/5/2023	Civil society: environment	Interview

Observations

#	Date	Event	Info on actors in involved
1	9/9/2022	SUNER-C board meeting	Research, civil society, industry
2	12/9/2022	SUNER-C WP6 meeting	Research, civil society

#	Date	Event	Info on actors in involved
3	13/9/2022	Bellona Europa: Decarbonising Europe's largest industrial cluster	Research, civil society, industry
4	27/9/2022	SUNER-C kick-off day 1	Research, civil society, industry, governmental
5	28/9/2022	SUNER-C kick-off day 2	Research, civil society, companies
6	6/10/2022	SUNER-C WP6 meeting	Research, civil society
7	27/10/2022	EURACTIV Hybrid conference: How to ramp up hydrogen production & speed up the steel industry's transition'?	Research, industry, public
8	8/11/2022	SUNER-C steering group Ghent University	Research
9	15/11/2022	Moonshot for Industry – CATALISTI – MOT3: Electrification & Radical Process Transformation	Research, industry
10	18/11/2022	Hydrogen Platform Ghent University	Research, industry
11	21/11/2022	SUNER-C WP6 internal workshop socio-technical issues	Research, civil society
12	22/11/2022	SUNER-C WP6 meeting	Research, civil society
13	23/11/2022	SUNER-C WP7 stakeholder workshop priorities and vision	Research, industry
14	13/12/2022	SUNER-C steering group Ghent University	Research
15	15/12/2022	What's up with Project One? By Ineos Will Fall and Climaxi	Research, civil society
16	21/12/2022	SUNER-C WP6 meeting	Research, civil society
17	30/1/2023	ArcelorMittal: company presentation for the Climate Forum of Ghent	Research, civil society, industry, governmental
18	9/3/2023	Carbon Capture and Storage Association & Zero Emissions	Civil society, industry, governmental

#	Date	Event	Info on actors in involved
		Platform webinar: building a European CO2 transport and storage infrastructure	
19	21/3/2023	EurActiv Debates: CO2, H2 AND O2 cornerstones of the energy transition	Civil society, industry, governmental
20	21/3/2023	SUNER-C WP6 meeting	Research, civil society
21	24/3/2023	Hydrogen Europe: Clean Ammonia in the Future	Industry
22	27/3/2023	European Commission's CCUS Forum - WG on Public Perception	Research, civil society, industry, governmental
23	13/4/2023	Sustainable and low carbon fuels and chemicals - time for take off (CEA event)	Research, civil society, industry, governmental
24	25/4/2023	Hydrogen Europe: The role of hydrogen-based fuels in decarbonizing EU aviation	Industry, governmental
25	10-11/10/2023	Yearly SUNER-C General Assembly	Research, civil society, industry, governmental