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Emission reduction targets and electrification of the Finnish energy system with low-carbon Power-to-X technologies: Potentials, barriers, and innovations – A Delphi survey

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ABSTRACT

Energy systems are rapidly changing, and many promising low-carbon solutions are now available for different industries. For a society to efficiently implement these promising technologies, experts and policymakers from different fields must comprehensively understand the possibilities and barriers of these technologies. This paper investigates how experts in different fields perceive the transition by conducting two broad Delphi surveys regarding energy transition and greenhouse gas emission targets in the context of Finnish society. The focus of the research is Power-to-X technologies, the required actions and barriers for achieving emissions targets, and societal electrification. The results reveal that while it is possible to achieve the ambitious emissions targets, a variety of political and technological changes are required. It is also established that Finnish society will increase low-carbon electricity consumption in the near future. For instance, Power-to-Gas and Power-to-Fuel technologies are viewed possible technologies for achieving the targets.

1. Introduction

Climate change mitigation and related shifts in energy systems, which could significantly lower CO_2 emissions, are subjects of increasing international academic and policy focus. Energy technologies are being developed and refined to produce energy from renewable resources and provide energy services according to the demand patterns (Aghaei and Alizadeh, 2013). Such transitions are known as electrifying energy systems (Baruah et al., 2014; Davis et al., 2018). Furthermore, 100 % renewable energy (RE) systems are shown to be both economically and technologically feasible (Mathiesen et al., 2011; Child et al., 2019). Simultaneously, energy demand reduction is purportedly an essential component of climate change mitigation, placing focus on energy efficiency in areas such as construction and mobility (Ürge-Vorsatz et al., 2011; Colmenar-Santos et al., 2019). Nonetheless, energy systems connect to multiple technical systems, policy-processes, market structures and culturally rooted practices; hence, their development has been analysed from socio-technical transition perspective, which implies that any advancement towards a broad adoption of energy systems with low CO_2 emissions must be analysed from a considerably broader perspective instead of simply the technological perspective. (Simmie et al., 2014). Numerous technological and practical solutions for mitigating and adapting to climate change have been developed to support on-going energy transition. Solar photovoltaic (solar PV) and wind turbine technologies are some of the well-established examples, which have rapidly increased global capacities due to the drastic cost reduction (Barbose and Darghouth, 2019; He et al., 2020). The rapidly expanding markets for these two energy production technologies have not occurred without support; incentives; moreover, research and development (R&D), funding and the changing social acceptance of the implementation of these technologies have affected their success in energy markets (Elia et al., 2021; Saidur et al., 2010; Solangi et al., 2011; Chen et al., 2014). However, wind and solar energies tend to fluctuate, bringing new challenges related to grid balancing and providing stable power. If these challenges cannot be solved, there is a risk of failure to establish a stable energy system, which could lead to a failure of power systems emission reduction targets. Fortunately, there are solutions to these challenges. For example, providing energy storage, peak power, and emergency power facilities, and implementing diverse demand response solutions can be used to balance the grid (Sinsel et al., 2020).

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One interesting family of cutting-edge technologies that could be part of the solution to these challenges is Power-to-X (PtX) technologies. The term 'PtX technologies' refer to several technological solutions that produce something from electrical power and transform the product back to electricity, if necessary. A typical definition of PtX technologies refers to the use of RE to power energy conversion (Daiyan et al., 2020).

In addition to various PtX technological solutions, an abundance of products exists that could be produced via PtX technologies, including power-to-food (PtFood) (Sillman et al., 2020), Power-to-Gas (PtG), Power-to-Fuel (PtFuel) (Uusitalo et al., 2017), and Power-to-Ammonia (Ikäheimo et al., 2018). Some PtX technologies, such as Power-to-Heat (PtH) (e.g. heat pumps), are already widely implemented and developed technologies, but the majority of PtX solutions are currently under R&D and piloting phases (Chehade et al., 2019). In many cases, the products from PtX technologies using renewable energies have been shown to emit a lower amount of greenhouse gas (GHG) than counterpart products in the same markets. However, in many cases, the RE source is the boundary condition for PtX technologies' claims of environmental sustainability (Zhang et al., 2017; Sillman et al., 2020; Uusitalo et al., 2017). As the potential of PtX technologies is evident, and such solutions have sound mitigation and even adaptation prospects for addressing climate change, their acceptance, readiness and potential barriers to implementation in grid systems are of interest. Specifically, many PtX technologies are still in the R&D phase and their implementation depends on how the RE markets develop (Chehade et al., 2019; Skov et al., 2021).

Promising technologies such as PtX develop through systemic interdependencies, which give recognition to, share knowledge about allocate assets and create demand for the technologies. These processes have been theorised as technological innovation systems (TIS). Carlsson and Stankiewicz (1991) define TIS as 'a network or networks of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilize technology.' Furthermore, TIS has also been defined as a list of functions (Bergek et al., 2007; Hekkert and Negro, 2009), which include functions of 'Knowledge Diffusion through Networks' and 'Guidance of the Search' for directions, timelines and targets for technology deployment. The need to manage expectations and direct efforts in technology development is stressed in sustainability transition scholarship beyond TIS. Multiple different pathways for technology development (Geels and Schot, 2007) imply inherent openness and uncertainty and competing promising innovations (Köhler et al., 2019) as active work and enactment of unfolding paths (Geels et al., 2016). A lack of shared visions constitutes a potential transformation failure of sustainability transitions (Weber and Rohracher, 2012). Thus, transition research highlights how technological solutions are selected and amplified by considering the plausible futures, existing barriers and essential constituents of socio-technical change. Therefore, energy transition presents a constructivist view that includes both technical and social change, recognising the influence of discourses in guiding thought, speculation and R&D (Elzen and Wieczorek, 2005).

Although obvious linkages exist between future study methods and transition scholarship, still many dimensions, e.g. different dynamics in sustainability transitions, require further insight (Vähäkari et al., 2020). However, energy transition and its societal implications are being increasingly investigated (Revez et al., 2020). This study contributes to the literature by considering the potential of using future study methods, specifically a Delphi survey, to generate and distribute knowledge of technological innovations and contribute to consensus and shared expectations among technology developers. The Delphi method allows participants to gain insight and share perspectives and feedback, which can be used to develop conclusions regarding the various factors affecting the topic of investigation (Himanen et al., 2016). The method has been described as an iterative and anonymous tool for structuring the views of groups and experts regarding a complex problem (Linstone and Turoff, 1975). Furthermore, it has been used to obtain opinions from and share them among different stakeholders and experts regarding specific topics (Flostrand et al., 2020; Rikkonen and Tapio, 2009). Additionally, it has been demonstrated that groups using the Delphi method can derive better outcomes than staticised or standard interacting groups when conducting forecast studies (Rowe and Wright, 1999). Hence, Delphi studies can help create a shared understanding of unfolding transitions and technological search heuristics and thereby directing innovation activities.

For energy transition studies, the Delphi method has been typically used to design future scenarios and forecast emerging and evolving energy-related technologies and innovations (Chen et al., 2020; Nowack et al., 2011; Revez et al., 2020; Winskel and Kattirtzi, 2020), making the method well suited for this study. Previous Delphi surveys exploring energy transitions have typically studied energy policies and subsidies of RE sources and the share of RE production. Moreover, some have focused on a specific topic in energy transition such as business opportunities in farms or aiding scenario planning (Chen et al., 2020; Czaplicka-Kolarz et al., 2009; Rikkonen et al., 2021; Winskel and Kattirtzi, 2020). To the authors' best knowledge, no Delphi studies have been conducted focusing on the implementation of PtX technologies or the energy transition in the context of carbon-neutral targets (See Section, Delphi and Energy transition).

There are several ways to approach PtX technologies in future studies. It is possible to focus on narrow technical knowledge on conversions between different energy carriers and energy embodied in different materials, but also to broader knowledge of the conditions of a change in the energy system. Such broader knowledge includes understanding the need to match market supply and demand and articulating new visions and paradigms, such as the electrification of the energy system. Accordingly, such an innovation network's composition and relevant members are not fixed. Specifically identifying actors in the early phases of technology development is difficult (Bergek et al., 2008). Such difficulties also relate to the Delphi survey method and recruitment of participants and will impact substantive results in helping to share knowledge of emerging technologies for sustainability transitions.

This paper reports the results of two Delphi surveys conducted in 2016 and 2019, regarding implementing PtX technologies, societal electrification and emissions targets in Finnish society. The survey was conducted with experts in energy transitions in Finland as part of the 'Smart Energy Transition' project. The project sought to explore the significance and possible ramifications of global energy technology development for Finnish energy systems, including production, transmission and end-use, different business sectors in Finland, global demand, and competencies of Finnish actors in energy solutions. As the topics of electrification and implementation of low-carbon technologies can be considered global megatrends, the results regarding technologies, policies, barriers, and enablers are potentially applicable for many countries other than Finland (especially in the European Union [EU]) to help identify the critical factors in energy transition, thus helping policymakers. Additionally, as only limited amount of Delphi studies investigating energy transition exists, this study provides valuable insight for future studies.

2. Materials and methods

This section reviews the history of the Delphi and its use to gain insight into energy transition. Subsequently, the planning of the presented study is explained.

2.1. Delphi and energy transition

The Delphi method was developed during the cold war by the Rand Corporation in US to evaluate the Soviet's nuclear weaponry capacities and usage possibilities (Dalkey and Helmer, 1963). Following publication, the method has been used regularly to forecast possible development and to find a consensus of expert opinions on problems that are hard to predict using empirical or statistical data. Although the Delphi method is typically used in health care, education and business, it is increasingly used in engineering, technology and environmentanl studies (Flostrand et al., 2020). This study investigates the issues related to energy transition, including the technology, policy, barriers, environmental and economic aspects. Several Delphi based studies have been conducted on energy transition in recent years. However, the contexts differs from this study or topics are narrowed down to focus on a specific technology or opportunity. The following small literature review helps outline and position the dimensions and questions that can contribute to the on-going discussion on energy transition in this study.

The Delphi method can be used for scenario planning, for example, to study how technologies and innovations are expected to develop in the near future (Renzi and Freitas, 2015). Rikkonen et al. (2021) presented five scenarios, namely, business as usual, energy savings and decarbonisation, climate-friendly transformation, green growth and degrowth, on how the share of RE develop in Finland until 2030. The presented scenarios were based on conducted Delphi surveys in their study. The share of renewables increased in each scenario, but the total energy consumption varied radically from 200 to 420 TWh depending on the scenarios. Regarding the RE transition, there were different views on whether short- or long-term support would be the best way to trigger the change. However, the focus was on subsidies or investment aids. The other means, such as taxes or banning the most harmful practices, were neglected. Additionally, the common view was that climate policy and targets would become stricter but means for different industries to achieve those goals were not evaluated. Chen et al. (2020) used the Delphi method to create scenarios of how different RE sources will develop by 2030. The dimensions were divided into social, technological, economic, environmental, and political fields. Financial incentives and environmental regulation were seen as efficient policies to promote an increase in renewables in Chinese energy systems. Interestingly, less than 50 % of the respondents thought an emission trading system was an efficient policy. The key drivers were the breakthrough in RE technologies, growing ecological awareness and national energy pricing.

Many Delphi studies on energy transition narrow down the topic to gain insight into the opportunities the transition can provide from an enabler or technology perspective. Winskel and Kattirtzi (2020) presented the results of a Delphi survey on the smart and local energy revolution in the UK. The respondents anticipated that in some areas, there will be more distributed energy system governance and flexibility locally by 2040 than currently, but a need for national measures still exists. The respondents also thought that the demand side management and response and local storages play a significant role in future energy systems. Annala et al. (2018) gathered information from various sources, including a Delphi survey, to analyse barriers to utilising demand response solutions in Finnish energy systems. The main barriers were found to be technical issues and end-user incentives. Rikkonen et al. (2019) presented the results of a Delphi study on how small-scale RE production can bring new opportunities to Finnish farms, and Varho et al. (2016) focused on distributed small-scale RE in Finland. Ghadami et al. (2021) used the Delphi method to investigate how to motivate citizens to increase household solar energy use. The focus was on different direct or indirect subsidies that the citizens can receive when using solar energy. Regarding hydrogen production technologies, which are tightly related to PtX technologies, Chang et al. (2011) investigated the technologies that should be chosen for future development using the fuzzy Delphi method. The outcome of the study was hydrogen generation via wind and solar energies.

2.2. Planning and topics of the surveys

The energy transition as a topic was vague during the planning phase of the project 'Smart Energy Transition' in years 2013–2014. There were discussions on determining the used method for gaining the insights into the possible future developments. The aim was to investigate how meaningful the energy transition can be for Finland. Moreover, as in many cases, when a transition occurs, it is thought that similar perceptions on the paths and qualities of the transition can support the transition. As the Delphi method is widely used in foresight studies and helps in consensus forming (Makkonen et al., 2016), it was chosen to investigate the possible transition in Finland.

Typically, only a single Delphi survey is conducted and reported at a time (e.g., Himanen et al., 2016; Chen et al., 2020). The topic of energy transition is broad and includes many subtopics and contexts. Thus, it was decided to conduct two Delphi surveys for the Smart Energy Transition project to keep the number of questions manageable per survey round. It has been shown that conducting one extensive Delphi survey can make the Delphi process too heavy for the respondents. Heavy surveys can lead to reduced participation rates and negatively affect the quality of the answers, which has been shown to be the case in some large-scale Delphi surveys (Belton et al., 2022). Another reason for conducting two separate Delphi surveys is the rapid development of energy transition, seen in the increase of RE capacities. If an unforeseen and profound development or technology emerges during the Delphi process, it is easier to adjust the survey with sufficient background information by starting a new survey than trying to fit them all into one.

This study focuses on questions related to PtX technologies and the factors affecting the implementation of those technologies, such as emission reduction targets. The surveys were conducted in Finnish and English, and the data of the translated results and questions are presented in the Supplementary materials. The process of planning the surveys was iterative and consisted of expert interviews. The respondents answered anonymously, and the surveys were sent to the same group of experts for each round. There was an opportunity to comment freely on the topic asked in each question.

The first survey was based on issues and questions that emerged through expert interviews and a brainstorming workshop, during which the critical energy transition topics identified were solar heat and thermal energy systems, solar-based electricity, biomass-based energy, digitalisation, and demand response solutions. The workshop included a panel of experts from different fields of the Finnish energy sector. The workshop participants were energy-related experts with diverse work backgrounds in technology, policy, markets and managers to provide multidisciplinary responses. The workshop participants recognised personnel to whom the surveys were sent. As the topics were broad, the respondents were able to skip questions if their expertise was not suitable and were given one month to return their answers. After each survey round, the results were analysed and presented to a panel of experts, which impacted the contexts of the following surveys (Fig. 1). The draft versions of the new question rounds were evaluated and improved with the help of the panellists before sending them to all recognised personnel. The surveys were conducted using Delphi Method Software, an online tool designed for Delphi surveys (https://www.edelphi.org/).

Following the first survey, another meeting was held with experts in 2018 to plan the second survey. During the planning phase of the second survey, the Finnish government set new targets for a carbon-neutral society by 2035 (Ministry of the Environment, 2021). Therefore, the focus of the second survey was to investigate how and whether carbon neutrality can be achieved by 2035 and to provide that information to the decision-makers. In addition, the results and comments from the first survey indicated a need for questions related to barriers and innovation, another focus of the second survey. The first part of the second survey included context and transition factors, technologies, enablers and barriers, organisational innovations and background information of respondents. The second part was divided into three sections, the significance of different barriers to achieving carbon neutrality, the potential of different technologies and background information of respondents. Relevant background information regarding the definition of carbon neutrality and PtX technologies were presented to the respondents before the survey. Here carbon neutrality can be achieved using

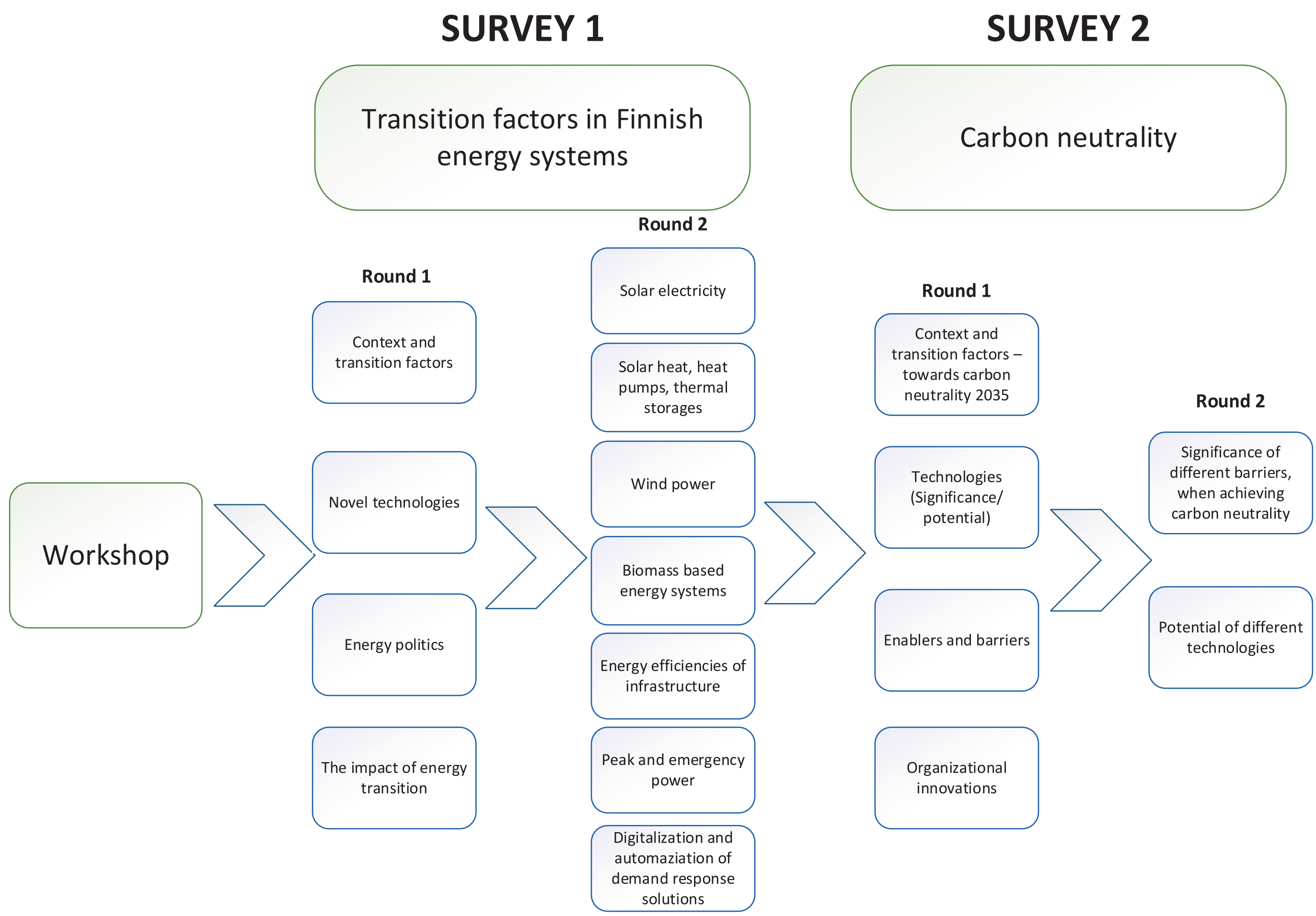

Fig. 1. The contexts and planning of the Delphi surveys. After each phase, the surveys, meetings and workshop outcomes were analysed and impacted the contents of the following phase.

compensation to achieve net-zero carbon equivalent emissions, similar to Natural Capital Partners' (2020) definition.

2.3. Categorisation of the questions

The questions were divided into three categories based on topics and contexts to enable clarity. However, all questions and responses of the two surveys are not presented in this paper. Questions requesting more detailed information on specific technologies than already asked and not directly related to demand response solutions or PtX technologies were neglected. For example, the authors presented the question and answers of how the respondents predict that solar energy from photovoltaics will increase in Finland but did not present the results of a question asking about the share of integrated solar panel systems on buildings from total solar energy generation. The first and second categories contained questions focusing on issues affecting the implementation of PtX technologies related to societal electrification and emissions reduction targets.

Generally, PtX technologies can be applied in many ways, including in the production of a diverse array of low-carbon products (de Vasconcelos and Lavoie, 2019; Bailera et al., 2021), as a demand response solution (Burre et al., 2019), or to produce an energy source for energy storage for grid balancing, such as gas-to- gas turbines (Buttler and Spliethoff, 2018; de Vasconcelos and Lavoie, 2019). Overall, PtX technologies can be considered one of the critical technologies for societal electrification (Schnuelle et al., 2019), and requirements for decarbonising products and services and demand response solutions for balancing the grid favour the implementation of PtX technologies. Nevertheless, implementing hydrogen utilising PtX technologies was unpopular when the surveys were conducted. Readiness, potential and willingness to use PtX technologies must favour the implementation. Subsequently, the third category asks about barriers, potentials and other relevant matters related to PtX technologies. (Fig. 2). The questions and their contexts are presented in Tables 1 and 2 and categorised as shown below.

The first category comprises the following:

- The desirability of the so-called new wave of electrifying energy systems.
- The need for demand response solutions.
- Factors accelerating the energy transition.

The second category comprises the following:

- Factors affecting emission reduction targets.
- The transition and timeframe towards a carbon-neutral society.

The third category comprises the following:

- The roles of different PtX technologies in future Finnish energy systems.
- The existing barriers and organisational innovations for PtX technologies.
- The potential of different PtX technologies.

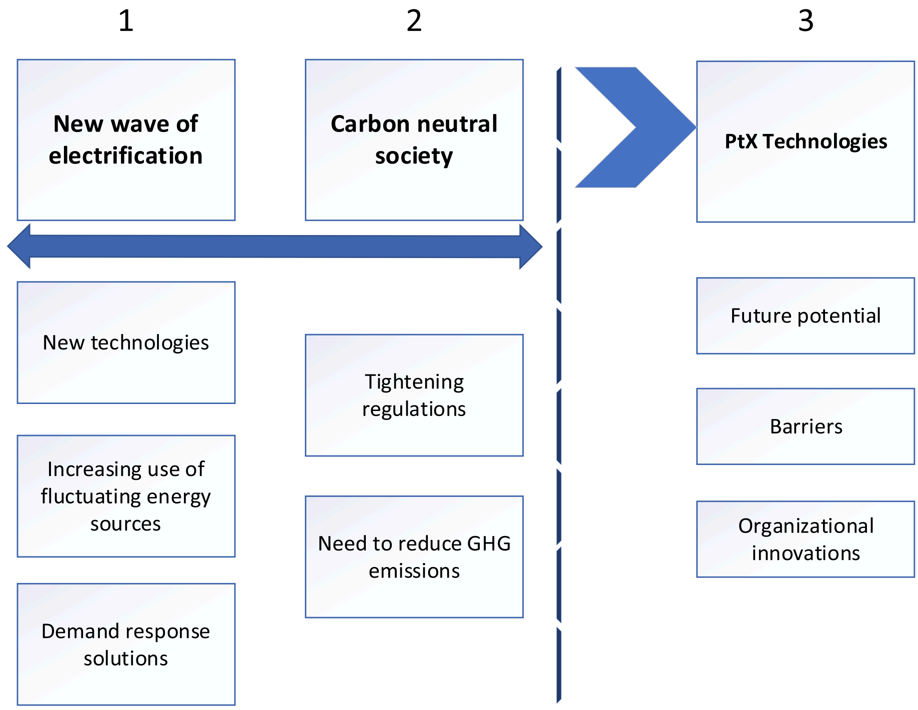

Fig. 2. The categories and context of the questions and their relationship.

Table 1
Survey 1 questions, contexts and categories.

Questions	Contexts	Category
Survey 1.1		
1.1.1: Electrical energy consumption in 2030 in Finland	Decrease or increase	I
1.1.2: The new wave of electrification in 2030	Not happening or going to happen	I
1.1.3: Transition factors: Capacity markets for electricity	Not happening or going to happen	I
1.1.4: Transition factors: The increasing role of consumers	Not happening or going to happen	I
1.1.5: Tightening regulations for allowing carbon dioxide emissions in 2030	Not happening or going to happen	II
1.1.6: Transition and transition factors of energy systems	Oppose or increase the transition	II
1.1.7: The significance of the new technologies in 2030 in Finland	Significance	I/III
1.1.8: Greenhouse gas emissions targets in 2030 in the EU	Achieved or not	II
1.1.9: Greenhouse gas emissions targets in 2020 in Finland	Achieved or not	II
1.10: International emissions trading system	Achieved or not	II
1.1.11: Policy actions to support energy transition	Should not be used-should be used	I/II
Survey 1.2		
1.2.1: Solar electricity	Significance	I
1.2.2: Wind energy	Significance	I
1.2.3: Peak power and reserve power in 2030 in Finnish energy systems	Amount – Significance	I
1.2.4: Peak power and reserve power: The importance of domestic emergency power	Importance	I
1.2.5: Peak power and reserve power: The importance of demand response solutions	Importance	I
1.2.6: Peak power and reserve power: The importance of energy storages	Importance	I
1.2.7: Digitalisation and demand response solutions as an energy solution	Significance	I

2.4. *Background information for each survey*

Most respondents worked in the private or academic sectors (Table 3). The numbers represent the total number of respondents who completed each survey. Although the number of respondents decreased across the survey rounds, the ratios of different workplaces remained relatively the same. The exception was the last survey, where the proportion of respondents with academic backgrounds was larger than those in the private sector. The respondents were also asked about their level of expertise, age, position in their profession and gender. This information can be found in the supplementary materials.

The possibility exists for biases and subjective opinions of the expert panellists who formulated the questions and the experts who responded to the survey, presenting a challenge related to the technological insights identified (Bonaccorsi et al., 2020). This issue can be partly tackled by including experts with diverse backgrounds in the survey and analysing whether notable differences exist in the responses depending on the respondents' backgrounds. This analysis was performed for a few questions in each category, and the results are found in the Results section.

3. Results

The data of the results for each category are presented in the supplementary materials. Some questions contain topics related to more than one category. The categories can be identified below the questions. In these cases, the result of each specific question is presented only in the first table mentioned. The possibility of biases and subjective opinions based on the respondent's backgrounds was studied for a few questions. The comparison showed that the results were homogenous between the respondents with different backgrounds (workplace, position in the profession, education, level of expertise and age and gender). However, some slight differences were observed in some of the questions investigated. These differences are mentioned after the related results.

Table 2
Survey 2 questions, contexts and categories.

Questions	Contexts	Category
Survey 2.1		
2.1.1: Shall Finland achieve carbon neutrality by 2035?	Achieved or not	II
2.1.2: What industry sectors need to change to be carbon-neutral by 2035?	Requires changes or not	II
2.1.3: Should greenhouse gas emission amounts affect the price of the product or service?	Amount	II
2.1.4: The most significant technologies - Capacity in Finland in 2035	Significance	I/III
2.1.5: The potential of different Power-to-X technologies in Finland in 2035	Potential	III
2.1.6: Enablers for and barriers to the energy transition towards carbon neutrality in Finland	Supports or hinders	II
2.1.7: Organisational innovations to develop Power-to-X technologies	Importance	III
Survey 2.2		
2.2.1: When is it possible to achieve carbon neutrality?	Time	II
2.2.2: Actions needed to achieve carbon neutrality	Practices	II
2.2.3: Barriers to introducing new technologies	Significance	II/III
2.2.4: Barriers to the electrification of private cars in the transport sector	Significance	II
2.2.5: Barriers to change towards low carbon composition technologies of private cars in the transport sector	Significance	II/III
2.2.6: Barriers to change towards low carbon in the heavy transport sector	Significance	II/III
2.2.7: Peak power and reserve power: Domestic reserve power	Importance	I
2.2.8: Peak power and reserve power: Energy storages	Importance	I
2.2.9: End users of Power-to-Heat technologies in 2035 in Finland	Significance	III
2.2.10: PtG as a part of the energy solution in Finland in 2045	Not happening or going to happen	III
2.2.11: Power-to-Fuel as a part of the energy solution in Finland in 2045	Not happening or going to happen	III

Table 3
Background information for the respondents and totals.

	Private	Public	Academic	Non-govermental organisation	Other	Total
Survey 1.1	24	7	14	3		48
Survey 1.2	13	10	9	7		39
Survey 2.1	10	2	8	2	1	23
Survey 2.2	5	2	7		1	15

3.1. The results of the first category of questions

Most respondents thought the so-called new wave of electrification of energy systems was desired and would probably occur in Finland (supplementary material, 1.1.2); however, electrical energy consumption is not expected to increase in every sector. For example, most of the respondents contended that building and energy-intensive industries will not increase electric energy consumption in the near future (supplementary material, 1.1.1). Due to climate targets and market circumstances, the share of renewables was predicted to increase significantly in Finland, resulting in the need for demand response solutions (supplementary material, 1.1.7; 1.2.1–1.2.3.; 1.2.7; 2.1.4). Moreover, a need exists for capacity markets for electricity (supplementary material, 1.1.3) and rising peak and emergency power capacities (supplementary material, 1.2.4–1.2.6; 2.2.7–2.2.8). The background analysis showed that the private sector respondents saw a higher increase in market capacity of electricity compared with other respondents. The private sector also saw the share of solar electricity higher. Furthermore, the share of wind energy and peak and emergency power increase was viewed as being lower in the public sector and NGOs. Otherwise, there were no significant differences.

Further, R&D and pilot project funding were seen to be the most efficient policies to fasten the energy transition further. The feeding tariffs resulted in contradictory opinions. Approximately the same number of respondents viewed that it as an unusable policy action that should not be used (supplementary material, 1.1.11). As a transition factor, an increase in the role of consumers was desired and would further elaborate the transition (supplementary material, 1.1.4).

3.2. The results of the second category of questions

The results of the first survey indicated that the EU and Finland will achieve GHG reduction targets in 2030; however, the respondents also indicated that tighter regulations regarding emissions allowances should be implemented based on their comments and responses (supplementary material, 1.1.5, 1.1.8–1.1.10). Academic respondents considered it more probable that the GHG reduction targets would be achieved in Finland, whereas the private sector had more respondents who did not believe it. Conversely, the private sector viewed the role of the international trading system as being most important compared with others, and academic respondents saw it to be used together with other tools. Many comments referred to the need for required mitigation actions to keep climate change tolerable and implement the Paris agreement, which requires tighter regulations to succeed. The national and international regulations were considered one of the significant factors towards the transition of energy systems (supplementary material, 1.1.6).

The second survey focused on Finland's more challenging target of achieving carbon neutrality by 2035. Most of the respondents predict that carbon neutrality can be achieved, or will probably be achieved, for heat generation and electricity generation by 2035. However, for other fields, the respondents' predictions were not optimistic. Most respondents predicted that the transportation and building sectors cannot achieve carbon negativity targets (supplementary material, 2.1.1), indicating that the required changes would be too significant to implement by 2035. As uncertainty exists regarding whether carbon neutrality target can be achieved in the industrial, transportation, and building sectors, experts were asked to estimate when the sectors can achieve the target. For the industrial, transportation, and building sectors, the respondents predicted that neutrality could be achieved by 2040–2050 depending on the sector. Most respondents saw that the carbon neutrality of buildings can be reached by 2045 (supplementary material, 2.2.1). However, a few respondents with technology education and working in technology and education and private sector believed it can only be reached after 2050.

As the industrial sector includes many types of business, the respondents were asked about the achievability of carbon-neutral targets for each business separately, estimating how much the business must change from its current trends to be carbon-neutral. Accordingly, the respondents indicated that most industrial sectors require significant changes, implying high uncertainty regarding whether the targets can be achieved (supplementary material, 2.1.2). Moreover, as many industry sectors require significant changes to achieve carbon neutrality, it was asked what actions are needed to achieve it. The answers revealed a problematic issue, as no consensus emerged regarding feasible action (supplementary material, 2.2.2).

For achieving the new emission reduction target, the recognition of barriers and enablers is essential. According to question 2.1.6, the most significant enablers to achieving the targets are regulations and agreements implemented at the EU, national and international levels.

Although technological development is needed to meet the targets, policies were considered to be more significant. The biggest barrier was seen to be the already made investments in the old technologies. As the implementation of new technologies is related to transition and achieving carbon neutrality, identifying barriers related to the implementation is of interest. Based on the results, there are vast challenges to be solved before implementing these new technologies, such as companies' resistance to change and institutional constrains (supplementary material, 2.2.3).

Since the respondents highlighted the need for tighter regulations on emissions allowances for previous emission reduction targets in survey 1, we investigated how much GHG emissions should affect the price of a product or service to be carbon-neutral by 2035. If an emission allowance system is already practiced in the field, the current price is considered in the answers. The question also refers indirectly to an issue that is highly debated; whether the emission trading system should be expanded to other fields. This question focused solely on the price of carbon emissions and did not consider other possible ways to guide towards low-carbon products and services. The respondents indicated that each sector's current raised emission prices were inadequate. Depending on the sector, most respondents thought the emissions allowances should be raised between 1 and 50 % (supplementary material, 2.1.3).

Transportation accounts for 21.6 % of the emissions in Finland (Tilastokeskus, 2021). Since transportation does not fall under of the European emissions trading system, national fiscal means are currently in use. These approaches include annual CO_2-based taxation and subsidies supporting the purchase of new electric vehicles, with both supporting the electrification of a private car fleet in Finland. Since the electrification of the transportation sector can be seen as a significant contributor to carbon negativity targets, it is crucial to understand the barriers/challenges related to the electrification and implementation of the low-carbon solutions of private cars and heavy transportation. The primary barriers to change in the electrification of private cars included the high cost of required infrastructure and the inconvenience of recharging cars, combined with consumers' resistance to change. The high price of electric cars was considered a significant factor, as there were no inexpensive electric vehicles available during the Delphi survey. Political barriers and the high cost of using hydrogen were viewed as the main barriers to transitioning to low-carbon combustion technologies for private cars in the transport sector based on the share of 'very significant'answers. This suggests the importance and a great potential of legislation for supporting the use of low-carbon combustion technologies. Legislation and fiscal means could also ease the low number of gas distribution points, which was considered the primary barrier, based on the number of positive ('significant'or 'very significant') replies. The main technological and organisational barriers to transitioning to low-carbon technologies in heavy transportation were inadequate infrastructure and regulations. The overall profitability of using hydrogen or electricity as motive powers in heavy transportation was also considered a key barrier affecting uptake. Notably, heavy transportation covers a broad range, including trucks and utility vehicles used in city areas only in the daytime and trucks for long-range transportation needs. (supplementary material, 2.2.2–2.2.6.)

3.3. The results of the third category of questions

All the different PtX solutions were thought to have potential in Finland. However other than PtHeat technologies, PtX technologies were considered too immature and untested to be widely implemented by 2035. When asked about their implementation, the respondents commented that the timeline for these potential novel and undeveloped PtX technologies should be prolonged. Therefore, the timeline for some PtX technologies was shifted from 2035 to 2045 after the first round of the second survey. According to 72 % of the respondents the desired production capacity of PtG technology was predicted to be 5 %–15 % of gas consumed in Finland by 2045 and it will probably happen. For PtFuel, the required capacity was 5 %–15 % of the fuel consumed in Finland by 2045. It was estimated to have a lower probability of realisation than the PtG solution (supplementary material, 2.2.10–2.2.11). However, PtH is predicted to be a significant technology that has already replaced some current technologies (supplementary material, 1.1.7). In addition, PtH technology was considered to have multiple end users and the highest potential applicability among PtX technologies. Interestingly, possible end users for heat pumps were seen to be district heating providers, which would further electrify the heating sector in the future (supplementary material, 1.1.7, 2.1.4, 2.1.5, 2.2.9).

The organisational innovations needed and existing barriers are essential considering to realise the integration of PtX technologies in future Finnish energy systems. The most critical organisational innovations of PtX technologies are related to the increase in R&D to develop new energy conversion and storage solutions in Finland. Among other organisational innovations, the respondents considered them to have similar importance, apart from the developing of tailored approaches for financing SMEs supporting renewable technologies, which was considered the least important. (supplementary material, 2.1.7.) When considering the barriers to introducing new technologies, the respondents indicated that the most significant obstacles were companies' resistance to change, the inadequacy of existing infrastructure (e.g. the grid), institutional constraints, and capital, which were evaluated as either 'very significant' or 'significant'. Political constraints, such as directives and regulations, were also considered a significant barrier, but only a small share felt it was very 'significant' (supplementary material, 2.2.3). Regarding barriers to integrating of PtG solutions in the transportation sector, the lack of gas distribution channels and points was considered the most important factor (supplementary material, 2.2.5). There were no significant differences between the respondents with different backgrounds in the category III questions.

4. Discussion

4.1. Discussions on the results of category I

Many sectors mentioned in question 1.1.1 were seen to decrease their energy consumption in the future, which is a contradiction when considering the transition of electrifying societies. For example, there are targets to improve energy efficiency of buildings in Finland (Energy Efficiency Watch, 2020) to reduce energy consumption. The overall electricity consumption has decreased from the peak year 2006 (Tilastokeskus, 2022). However, a clear tendency exists to increase overall energy production to meet the demand due to increasing electricity needs in other sectors in the future (TEM, 2019), such as for the transportation sector. Notably, the question considering energy consumption between different sectors was asked before the new national target to be carbon-neutral by 2035 was set. Naturally, this increases the need to furnish the energy sector with low-carbon technologies faster than previously thought. This may further accelerate the societal electrification, as with the transportation sector.

The need to speed up the transition is evident, when comparing the responses of questions 1.2.4 and 1.2.5 in Survey 1 and questions 2.2.7 and 2.2.8 in Survey 2. The importance of energy storage and reserve power increased from the first survey. Two possible explanations exist. The technological development between the first and second survey has been more rapid than predicted. For example, there has been a radical increase of RE in the utility (Finnish wind power association, 2021; Energy Authority, 2021). Another reason is required significant changes in different energy-related fields to meet carbon-neutral targets, as is evident from question 2.1.2. This raises the question of whether grid operators and other actors in energy markets can maintain the development momentum needed to meet the targets. The identification of enablers and barriers is essential to avoid possible bottlenecks in transition. In category II/III related questions, these issues were broadly investigated.

4.2. Discussions on the results of category II

The results regarding the need for tighter regulations to succeed in mitigation actions are congruent with studies considering this topic in the EU and some other Delphi surveys considering energy transition (Pietzcker et al., 2021; Rikkonen et al., 2021). One possible action recognised in Survey 1 was to widen and tighten the emission trading system. In Survey 2, the proper cost of emissions was asked for different sectors. The answers strongly suggest a need to extend emissions trading systems to other fields than where it is currently practiced while simultaneously increasing the price of GHG emissions. However, if the price of the emissions would significantly increase, for example, up to 50 % for a service or product, it would raise a justified question about the willingness to pay such amounts if no easy alternatives are available. There can be political setbacks. For example, the unjust sustainability transition and socio-economic inequalities in France are thought to be reasons for the yellow vest movement (Martin and Islar, 2020). Thus, other means are preferred to be used along the rising emission prices. This issue was also considered in the comment section.

Rikkonen et al. (2021) Delphi study on energy transition sought insight into how subsidies or investment aids should be used to promote RE sources. However, as our study showed, focusing only on a certain type of action can result in a one-sighted conclusion. The use of many different actions, even within the same sector, to achieve carbon neutrality was well recognised in question 2.2.2. It reveals the challenge of planning broad schemes that include multiple types of business to achieve emissions reductions; thus, it might be better to make a tailored action for each business. This calls for strong communication between policymakers, experts of in each industrial sector, and other relevant stakeholders. In addition, the results reveal the problem of too generalised communication or plans regarding mitigation actions, as many opposing opinions even among experts, which can hinder the implementation of climate mitigation actions. For example, The Finnish climate change panel (2019) estimated that Finland can achieve carbon neutrality by 2035 but requires tighter climate politics. This contradicts how energy sector experts viewed this topic in the survey (Supplementary material, 2.1.1); thus, the communication between experts in energy and climate issues must be improved and broadened to gain reliable consensus.

4.3. Discussions on the results of category III

There have already been several demonstrations of cutting-edge PtX technologies in Finland, such as PtFood (Ruuskanen et al., 2021), PtFuel, and PtG (Vázquez et al., 2018). However, in most cases, PtX solutions remain in the piloting or demonstration phases, or lack feasible development status among different energy technologies (Chehade et al., 2019; Skov et al., 2021). The exception is PtHeat solutions. For example, heat pumps have already changed how consumers heat their homes in Finland, and the change has been rapid. In a little less than 20 years (2000–2018) approximately one third of the households started to use heat pumps in Finland (Sovacool and Martiskainen, 2020), which is a good example of successfully governed decentralised societal electrification and rapid development. However, heat pump investment costs are drastically lower than other PtX technologies due to the abundance of need to produce hydrogen; thus, a similar kind of consumer-driven societal electrification is unlikely. The investment cost of electrolyser is significant obstacle to the successful commercialisation of hydrogen-related PtX technologies with the high cost of electricity (Olabi et al., 2021). Still, the potential of PtHeat solutions was not ranked first in question 2.1.5 despite having already commercialised solutions. PtFuel technologies were ranked first, followed by PtHeat. The reason might be that the survey context was carbon neutrality, and PtFuel solutions can potentially substitute carbon-based fossil fuels, making it an interesting solution to mitigate climate. Especially, as Finland has a relatively high amount of biomass-based CO_2 point sources to obtain the required CO_2 for fuel synthesis. Notably, as PtX technologies are considered key solutions for decarbonising the energy sector, their readiness can affect the responses to questions regarding the carbon neutrality targets for different sectors, such as transportation or industry.

For PtG and PtFuel technologies, most respondents saw a moderate role in the Finnish fuel and gas markets. If the implementation succeeds, it will profoundly change the Finnish energy markets and improve domestic energy security. However, wide implementation of different PtX solutions requires an additional rapid increase in RE and other low-carbon energy source investments in the Finnish energy grid to succeed. Regarding the utilisation of PtG as a part of the Finnish transportation sector, the distribution channels were seen to be the biggest obstacle. This is understandable, as the availability of distribution channels varies greatly depending on the Finnish region. The northern part of Finland has no gas distribution channels for the transportation sector due to the long distances between residential areas. For the southern parts, many distribution channels already exist (Gasum, 2021); thus, the feasibility of implementing of PtX technologies can depend on the region. The power-to-hydrogen solution was not considered an economically feasible option, and the economic aspect of power-to-methane was divided among respondents. In regions with well-developed distribution channels, such as Germany, the potential of PtG solutions can be higher that of Finland.

4.4. Reliability and further research

Due to the broad context of the study, the questions were irregular hindering the analysis of the results. If the questions had been structured in consistently, the surveys would have become too laborious for respondents. For example, if question 2.2.2 had been broken down to ask separately the significance of each action suitable for each energy-related field instead of asking the most suitable actions for each field, there would have been ten questions instead of one. Nevertheless, breaking down the Delphi into two separate surveys with time delay did not stop this study's reduction in response rates. This dilemma could have been tackled by using structured nominal group techniques, but it would have been difficult to arrange regular face-to-face meetings with all the participants. In addition, the context changed after the first survey due to changed national emission reduction targets set by the Finnish government; thus, the time delay between the Delphi surveys helped to adjust to the situation, which proved to be an advantageous practice. However, the contextual differences between the first and second surveys must be kept in mind while exploring the results. For example, as the emission reduction targets changed after the first survey, the required phase of the transition and required policies also changed as was shown to be the case regarding the question about the importance of domestic reserve power and energy storage.

Another advantage of conducting two Delphi surveys on the same topic with different contexts and a time delay is that the first survey can be used to evaluate the credibility of responses by assessing how well the respondents predicted the development of the near future. The first survey was conducted in 2016. Since then, Finland has increased the PV and wind turbine capacity from 27 MW to 198 MW (Energy Authority, 2021) and 1300 MW to 2250 MW (Finnish wind power association, 2021) from 2016 to 2019. Simultaneously, demand response markets have rapidly developed (Ruggiero et al., 2021; Valtonen et al., 2017). The respondents' answers are congruent with studies demonstrating the required changes for the grid to function with high shares of fluctuating energy sources (e.g. Müller and Möst, 2018). For example, the need for the increasing demand response and energy storage solutions is a similar perception than Winskel and Kattirtzi, 2020 presented. Overall, the increasing shares of RE and required changes for the grid was well notified in Survey 1. Some variations exist in the respondents' answers to the first category-related questions, but no huge differences were recognised. Notably, there were almost no differences between the most opposing answer possibilities in technology-related or energy-related questions, which indicates that different foundational expertise elicits similar opinions regarding the new wave of energy systems. For example, out of 55 responses, one predicted that the electric consumption in housing buildings would decrease significantly, and zero predicted that the energy consumption would significantly increase in 2030 (supplementary material, 1.1.1).

The subject of carbon neutrality is more complex than better understood topics, such as, the asked questions on the emission reduction targets in the EU level or the predicted increase of RE in the near future. The topic's novelty can explain that the responses to category II-related questions were more diverse than the better-known first category. In addition, the knowledge of carbon neutrality can be out of scope for some respondents, although climate issues and the energy sector are tightly interconnected. For example, according to background analysis academic personnel view the achievability of emission targets slightly more positively than the private sector. This difference could be explained by arguing that academic personnel know that available technologies exist for different challenges. However, the private sector might struggle to commercialise these solutions and investment needs. There were also questions that might be considered a conflict-of-interest topics. For example, further tightening of the carbon credit system will impact companies in the private sector. Regarding the questions in category three, fewer respondents answered those questions than did the other two categories. This is not a surprise, as many PtX technologies are immature and not yet commercialised. Further, there were no significant opposing opinion differences indicating that the quality of the answers was good in category three questions.

According to the responses, many different PtX technologies other than PtHeat or PtG, such as PtFood, have future potential in Finland. However, due to the broad context of the surveys, we could not fit all the relevant questions in the Delphi surveys. Similarly, the specific barriers, organisational innovations and other considerations related to some specific technologies were neglected. In addition, one of the main dimensions was emission reduction targets and Finland in the first and second surveys, which are location specific. This calls for more specific TIS studies on different PtX technologies with different dimensions. Particularly, the carbon neutrality dimension requires further investigation in different locations. Especially, because many technologies can have a higher emission reduction potential in other locations than Finland has, as Finland has already proceeded relatively far in emission reduction targets and clean tech implementation. Regulation, barriers and enablers are more location specific than technologies, which should be noted. However, Finland is part of the EU, and there are similar modern societies with similar technological readiness and policies; thus, many investigated regulations, barriers and enablers are also valid in other locations, such as Sweden. However, differences exist. Regardless, many of the results presented can be used as a core to plan future energy transition studies.

The results reflect expert opinions in the years following the Conference of the Parties Paris agreement in 2015 until the second survey in 2019. This is an era when global climate policy seemed to gain momentum. In 2022, the war in Ukraine has heightened concerns over energy security and the need to move from fossil fuel use and promote a transition to RE systems to unprecedented levels. For example, domestic energy reservoirs have become increasingly crucial in Finland; however, as fossil fuel prices rise, many European countries may invest more urgently in REs to reduce dependence on fossil fuel imports from Russia. This can further hasten the transition to carbon-neutral energy systems with PtX solutions. New surveys must be conducted to gain a better understanding regarding the impacts of the war on energy markets. Still, the results can be used to construct various scenarios for energy transition or as a basis for further discussion regarding key policies for achieving emissions targets. As the surveys revealed the need for wide implementation of technologies that increases the overall electricity consumption in the Finnish grid system in the future, the current increase in RE capacity is inadequate to meet potential demands; thus, future research and investments should focus on actions to accelerate the implementation of RE. As Finland is part of the EU, and similar issues regarding the readiness of PtX technologies, required technical solutions in highly fluctuating grids and tightening emission reduction targets, the questions and responses are relevant to many other nations struggling with the same issues, especially European countries with high shares of RE sources. In summary, as this is the first Delphi-survey on some of the topics, such as carbon neutral targets in a societal level and PtX technologies, the survey's results can be regarded as a discussion opener.

5. Conclusion

According to the results, there is a consensus among energy-related experts from the academic, private, government, and NGO sectors regarding the challenges and opportunities of low-carbon technologies and GHG reduction targets in Finland. The electrification of the energy system and related PtX technologies were widely recognised as relevant by the experts; however, there is variation and a lack of consensus regarding how policies should be regulated to further accelerate development, in particular, regarding whether to use a 'carrot' or a 'stick' for different sectors. The variety of potential carrots and sticks further emphasises the importance of on-going communication between decision-makers and relevant actors when designing new policies, as no single solution exists that can be applied to every sector. Most PtX solutions were evaluated to be too immature by 2035 but were predicted to have high market shares till 2045. Thus, the PtX technologies are predicted to penetrate the markets between 2035 and 2045. As PtX solutions are considered key technologies in electrification of societies, electrification can be predicted to develop rapidly after their successful commercialisation. Overall, this study provides valuable information regarding the pros and cons of different low-carbon technologies as well as possible barriers and required organisational innovations. The results further outline how significant the required changes are and how great the costs can be when targeting carbon-neutral societies. The costs can be too high for the citizens to accept the required policies successfully; thus, the information gained from the surveys can be used to build socioeconomically accepted roadmaps towards carbon neutrality with reasonable timeframes. Although the time delay between the two surveys did not affect the reduced response rates, it helped analyse how much the context impacts the need for certain technologies, such as energy storage and reservoir power, and helped to adjust the Delphi process in a changing environment. This kind of procedure can be beneficial in areas with rapid development phases.

CRediT authorship contribution statement

J. Sillman: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **K. Hynynen:** Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **I. Dyukov:** Validation, Writing – original draft, Investigation. **T. Ahonen:** Validation, Writing – original draft, Writing – review & editing. **M Jalas:** Conceptualization, Supervision, Validation.

Data availability

Data will be made available on request.

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.techfore.2023.122587.

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