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Shifting currents: Expert perspectives on the adoption of Direct Current in power grids[☆]

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ABSTRACT

Utilization of renewable energy resources for energy generation brought significant attention to Direct Current (DC) technologies, as many of them produce and store electricity in DC. Compared to Alternating Current, the DC technologies, specifically in Medium-Voltage (MV) and Low-Voltage (LV), are in their infancy, leading to less data availability for decision-making. To inform early-phase technologies, experts are consulted through the structured Expert Elicitation (EE) method, though few have explored it in examining technical and non-technical aspects of MVDC and LVDC technologies. Hence, in this paper, we present two EE studies on eleven (11) MVDC and LVDC technologies proposed in the Shift2DC research project — applicable for ports, buildings, industry, and data centers. We found that experts perceived the presented DC technologies as feasible and important. Among the most perceived concerns for DC technologies adoption are a lack of trained personnel, public awareness, and uncertainty in regulations to enforce the use of innovations. Experts proposed the need for educational strategies for the general public and a structured curriculum for training technicians in DC. In addition, experts envisioned enabling emerging technologies, such as digital twins and energy management systems, for DC system management.

1. Introduction

Report by the International Energy Agency (IEA) noted an increase of global energy demand to 2.2% in 2024, which is larger than the yearly demand average increase of 1.3% reported in the previous ten (10) years [1]. To meet the demand, literature highlights several sources of energy that have been explored. The focused energy sources include renewable [2] and non-renewable energy sources [3]. Example of Renewable Energy Sources (RES) includes wind, solar, and water [2,4]. Non-renewable sources include natural gas, fossil fuels like coal, petroleum, and natural gas [3]. However, non-renewable energy generation has drawbacks, including health and environmental issues [5]. Besides that, Carbon Dioxide (CO_2) emissions from non-renewable energy sources worldwide are approximated to 34 billion tonnes annually [6].

Hence, recent years have seen considerable efforts to improve the amount of RESs, which have much lower CO_2 emissions compared to non-renewable energy sources [2]. An interesting aspect of RESs and energy storage systems is that they naturally produce and store electrical energy in DC form [2]. Despite this, DC power has been traditionally established and utilized primarily for high-voltage, long-distance transmission since the mid-20th century [7].

Recently, however, the proliferation of DC-powered loads, such as LED lighting systems, Electric Vehicles (EV), DC motors, and other power electronic-based devices, has further driven interest in localized DC distribution [2,8]. Consequently, Medium-Voltage (MV) and Low-Voltage (LV) DC systems have been proposed — and, in some cases, implemented — to enhance energy distribution efficiency across various sectors, including buildings [9], data centers supporting the digital

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economy [10], marine power supply systems [11], and industrial applications [12]. Nevertheless, DC-based technologies are still in earlier stages of deployment compared to well-established AC systems [2].

Given that DC technologies, particularly at medium and low voltages, are still at an early stage of development, structured Expert Elicitation (EE) methods are often employed to address uncertainties related to their performance, costs, market potential, and adoption barriers [13,14]. While several EE studies have explored technical and economic aspects, fewer have examined the non-technical factors influencing DC technologies adoption [13]. Moreover, the literature highlights a notable gap in understanding these non-technical factors, specifically within microgrids, where MVDC and LVDC solutions are increasingly concentrated [12].

Hence, this paper examines experts' perspectives on technical and non-technical factors influencing the adoption of DC technologies through two EE studies. In these studies, we assessed the importance, feasibility, widespread adoption potential, associated risks, and barriers for eleven MVDC and LVDC solutions proposed under the Shift2DC research project. The project, funded by the European Union, focuses on introducing innovative approaches to power system implementation and on integrating MV and LV DC solutions into four key demonstration areas: ports, buildings, industry, and data centers [15]. The eleven DC solutions have wide application in four key demonstration areas of the Shift2DC project.

The first study involved DC experts within the project consortium, while the second engaged external DC experts. The primary motivation for conducting two studies was to enable iterative refinement of the elicitation protocol, as recommended in the literature [16]. Given that experts are often difficult to engage for iterative EE processes, literature suggests the use of *quasi-experts* (such as graduate students) to refine protocols when needed [16,17], though we were able to engage DC experts in both studies. Iterative refinement helps to prevent overloading experts by ensuring the amount and nature of information sought aligns with the limits of experts' availability and patience for the EE study [16]. Thus, the initial study served to identify key concerns and challenges, enabling improvements to the EE protocol before conducting the second, more targeted study.

The remainder of this paper is structured as follows: Section 2 presents background information and a literature review on expert elicitation in energy technologies. Section 3 describes the methodological approach for conducting the group-based elicitation studies and the software platforms employed. Both elicitation studies followed the same methodological framework. In Section 4, we present the findings of each study, with the second study building upon insights from the first. Section 5 provides a discussion of the results, supported by relevant literature. Finally, Section 6 offers the conclusions, lessons learned from both studies, and outlines directions for future work. For consistency, all DC devices, tools, and technologies discussed throughout the paper are referred to as *DC solutions*.

2. Background and related works

This section provides important background information on key considerations for conducting EE studies, as the literature suggests. It discusses critical factors such as ensuring a diversity of expertise, managing EE study budgets, and addressing the willingness and availability of participants. The section also reviews related EE studies in the energy sector and highlights how different elicitation parameters have been considered across the literature. Finally, it outlines the specific focus areas of the two EE studies presented in this paper.

2.1. Background

The EE methods have been widely used to capture expert perceptions in early-stage fields such as DC solutions [13,17,18]. EE is a structured approach applied across various disciplines to gather and synthesize insights on topics where empirical data may be limited, uncertain, or unavailable [13,17]. Through a systematic process, EE solicits and aggregates judgments from individuals with relevant expertise, knowledge, and experience in a specific domain [13,18,19].

The literature highlights various factors considered to decide on the number of experts for the EE. Including desired expertise mix, availability and willingness, budget, and time constraints [20,21]. Different academic publications present various stances on the number of experts for the elicitation study. Knol and Colleagues [22] suggest sufficiency of six (6) experts per study. Noting that with fewer than six (6) experts, the reliability of study results may be challenged. In addition, they claimed that exceeding twelve (12) experts tends to marginalize the benefit of the EE study [22]. Yet, several EE studies have recruited more than twelve (12) experts [9,13,14,20].

Obtaining diverse opinions in EE studies is crucial as they cover not only technical aspects but also non-technical ones like policies and social issues [13,20]. This is enhanced by consideration of diverse expertise [22]. In EE, [22] gave weight to the expertise mix by presenting three main groups of experts. First are generalist experts, those with a broad understanding of the topic. Then, normatives as experts with empirical and theoretical understanding of the topic. Lastly, the subject matter is for those with deep knowledge in the field. However, several elicitation studies [13,23] have recruited experts without justification of the three groups proposed by [22]. Most of the involved expertise in elicitation studies within energy fields are experts from universities, research laboratories and institutes, companies, energy policy, and climate change [13,20,23].

In individual EE, experts questionnaire via prepared online platforms or paper-based formats [24]. A disadvantage of this approach is the potential for biased data and the frequent need for *post-elicitation workshops*, which are follow-up meetings where results are presented to experts for feedback before being publicly released [25,26]. Such workshops are often resource-intensive [26].

Alternatively, group-based EE differs from less formal group information-gathering methods by following structured methodological steps that promote consensus among experts and highlight areas of disagreement [22,27]. The choice of elicitation mode depends on available resources, the geographic distribution of experts, and the capacities of the elicitation team [17,24].

2.2. Related works

In the energy sector, EEs has been widely explored due to the growing focus on the exploration and utilization of low-carbon energy sources, which has driven innovation in energy technologies to meet demand [2,4]. For example, EEs have been applied to nuclear power technologies [28], established and emerging Photovoltaic (PV) technologies [29,30], fuel cell technologies for EVs [14], and Carbon Capture and Storage (CCS) technologies [20]. The focus of each EE study depends on the specific needs and objectives of the research. For instance, some EEs aim to inform public policy [24,28,29], while others explore both technical and non-technical factors that hinder the adoption of new technologies [13,17]. Given the emergence phase of DC solutions, EE studies are particularly relevant for understanding the performance, adoption, and their future [9,12].

The work presented in this paper builds on previous EE studies in DC solutions, comprising both technical and non-technical aspects [13,17]. It is well-documented that the geographic locations and cultural backgrounds of experts can influence their perceptions [28], a claim that is also highlighted in [13]. But also, accessed EE papers are based in the United States of America (USA), and relied on DCs in buildings [9,13].

Table 1
Information of the elicitation studies.

Study	Experts #	Key topics	Time (min)	DC solutions
1	13	Feasibility and importance, time for widespread adoption, risk of non-availability, barriers to adoption (from other studies), additional barriers (experts' perceptions), open discussion.	120	Smart and sustainable DC cables, DC connectors, static protection system, semiconductor-based circuit breaker, protection DC system design tool, DC-DC converters, LVAC–LVDC interlink converter, DC measurement device, DC solution design tool.
2	11	Feasibility and importance, barriers to adoption (from other studies), additional barriers (experts' perceptions), open discussion.	90	Smart and sustainable DC cables, DC connectors, LVAC–LVDC interlink converter, network design tool for DC solutions, solid-state circuit breaker.

In this context, we conducted two EE studies to assess the importance, feasibility, risks, and perceptions on barriers surrounding the wide adoption of MVDC and LVDC solutions proposed within the Shift2DC project framework. This study specifically examines these parameters. Moreover, the project's broad use cases in four demonstration areas — ports, buildings, industry, and data centers add an important dimension to understanding the potential of these DC solutions.

3. Methods

This section outlines the methodological approaches used to prepare and conduct the two elicitation studies. It begins by introducing the DC solutions under study, followed by a detailed explanation of the elicitation protocol and the approach used to identify and recruit experts for the studies. The section also discusses the chosen elicitation mode and the software platform utilized. Finally, it provides an overview of the procedure followed to execute both elicitation studies.

3.1. Elicitation protocol

The elicitation protocol guides the study by indicating study descriptions and goals, parameters of interest, and the elicitation questions or questionnaires based on the selected parameters [23]. There are standard protocols like the 'Investigate', 'Discuss', 'Estimate', and 'Aggregate' (IDEA) protocol or classical model protocols [31]. But it is also a common practice for studies to customize related existing protocols used in similar fields [20,23]. The protocol used in this work was customized from different similar elicitation studies [9,13,21–23,32]. These descriptions are also found in the elicitation protocols referred to in Appendix C.

The selection of parameters for elicitation studies can follow different approaches. Some studies review related literature to identify relevant parameters and involve experts in the field. For example, [20] used a literature review to determine suitable measures, which were then converted into variables for the elicitation process in their study on CCS. Other studies use pilot studies to identify experts and clarify the parameters of interest, as well as refine the questions [32].

The parameters used in the two elicitation studies of this work are drawn from related literature referenced in each of the protocols, as well as the task objectives of the [15] project. The first and second elicitation protocols are outlined in Appendix C. The parameters for the first study include feasibility, importance, time for widespread adoption, risk of non-availability, barriers to adoption (from other studies), additional barriers based on experts' perceptions, and open discussion. Based on the results from the first study, the second protocol was developed. Challenges encountered during the first study included the length of the protocol and the clarity of some questions. As a result, the second protocol is an improved version of the first. The parameters for the second study include feasibility, importance, barriers to adoption (from other studies), additional barriers as perceived by experts, and open discussion. These parameters are summarized in Table 1 and detailed in Appendix C. The elicitation protocols were used to develop the questions for both studies, which are presented in Tables 2 and 3, respectively.

3.2. Experts recruitment

The approach of recruiting experts from these expertise areas has been employed in similar studies [13,20,23,33]. The designation of expert includes both technicians and individuals with advanced educational qualifications, working in companies that specialize in DC or have an interest in DC solutions, as demonstrated by Glasgo et al. [13]. These experts were recruited through a network of partners within the Shift2DC project consortium, as well as referrals from other practitioners and colleagues in DC and renewable energy solutions more generally.

Email communication was used to recruit experts and provide brief descriptions of the elicitation study. Experts were given options for dates and time slots, along with consent forms. These forms were reviewed and approved by the project authorities. To participate, experts were required to use an internet-enabled *second screen* (such as a tablet or smartphone) to answer the study questions. As applied in other EE studies [9,13,14,20], we imposed no limitations on the number of experts per study. As detailed in Table 1, thirteen (13) experts participated in the first study, nine (9) DC solutions were presented. The second study involved, eleven (11) experts, five (5) DC solutions were presented for evaluation. Also, Table B.8 in Appendix B provides in-depth descriptions of each of the DC solutions used in the two EE studies.

Experts self-reported their expertise at the start of each study. All experts were based in European countries and had extensive international experience in the energy domain. For the first study, expert expertise is summarized in Table 4: seven (7) in DC power electronics, two (2) in DC protection systems, two (2) in ports electrification, and one (1) each in data center electrification and academia. In the second study, expertise distribution is as follows: four (4) in DC power electronics, three (3) in academia/society, and one (1) each in ports electrification, buildings electrification, DC interoperability, and Alternating Current (AC)-DC power systems, as indicated in Table 5.

For easy understanding and linkage between the two EE studies. All quotes perceived by experts and discussed ideas have been coded. For instance, $\mathbf{S_1E_8}$ means, first study expert number 8. To know the expertise of that expert, the reader may refer to Table A.6 in Appendix A.

3.3. Elicitation mode and platform

For both elicitation studies, an online group-based mode was chosen. This mode is economical and allows for the engagement of geographically scattered experts without the scheduling challenges of in-person studies [34]. Additionally, research shows that both online and in-person modes yield comparable results [35]. Group-based elicitation also fosters consensus among experts, eliminating the need for resource-intensive post-elicitation workshops [25,26].

Regarding the platform and tools for conducting the studies, Microsoft Teams was selected to host the sessions. Teams provides a centralized workspace that supports real-time collaboration, communication, and integration with other applications [36]. To facilitate

Table 2
Elicitation protocol questions - First study.

SNo	Question	Options
1	Are you ready to start?	Yes, no
2	How FEASIBLE is the use of DC in the previously described demonstrators?	Not feasible, somewhat feasible, feasible, very feasible, not able to respond
3	How important is this solution? (For each DC solution in each of the three categories)	Not important, somewhat important, important, very important, not able to respond.
4	Barriers to adoption a total of eleven barriers were presented for experts to select all that they perceive applies	Select the top 5
5	When will we see a widespread adoption of these solutions? (for each of the DC solutions in each of the three categories)	<2030, 2030, 2040, 2050, not able to respond/never going to happen.
6	What is the risk of non-availability or delay in adopting these technologies? (for each of the DC solutions in each of the three categories)	Insignificant, moderate, critical, very critical, not able to respond.
7	Are there any other vital barrier(s) not listed?	Open-ended question
8	General discussion	Open-ended question

Table 3
Elicitation protocol questions — Second study.

SNo	Question	Options
1	Are you ready to start?	Yes, no
2	How FEASIBLE is the use of DC in the previously described demonstrators?	Not feasible, somewhat feasible, feasible, very feasible, not able to respond
3	How important is this solution? (for each DC solution)	Not important, somewhat important, important, very important, not able to respond.
4	Barriers to adoption a total of twelve barriers were presented for experts to select all that they perceive applies	Select the top 5
5	Are there any other vital barrier(s) not listed?	Open-ended question
6	General discussion	Open-ended question

Table 4
Experts for the first study.

S/No	Expertise	Count
1	DC power electronics	7
2	DC protection systems	2
3	Ports electrification	2
4	Data-center electrification	1
5	Academia/society	1

Table 5
Experts for the second study.

S/No	Expertise	Count
1	DC power electronics	4
2	Academia/society	3
3	Ports electrification	1
4	Buildings electrification	1
5	DC interoperability	1
6	AC-DC power systems	1

question-asking and polling during the studies, all questions in the elicitation protocols were coded in Slido, which enables real-time interaction in virtual meetings [37]. Finally, recordings and transcriptions of the sessions were managed using Read.AI, a tool designed for meeting summaries, transcription, and playback [38]. This combination of platforms ensured that the studies could run efficiently, with tools tailored to the specific needs of the elicitation process.

3.4. Elicitation procedure

The first elicitation study took place on Monday, 23rd September 2024, for 120 min, and the second elicitation study took place online on Friday, 25th October 2024, for 90 min, as indicated in Table 1.

Both studies followed the same procedure when conducting the elicitation study. The steps are elaborated below.

- The elicitation study started with a welcoming note from the elicitation team;
- Followed by a brief introduction of each participant, the elicitation team, and the participating experts. Information like names, expertise, and current job positions. Personal information shared has not been publicly disclosed, as informed in the consent form signed by each expert before each of the elicitation studies;
- Then, the start of the PowerPoint presentation, which had two parts.
  The first part of the presentation aimed at establishing rapport by familiarizing the experts with the study and providing an overview of the project and the DC solutions being studied [39]. Experts were then briefed on how the elicitation study would proceed. To ensure everyone was set up for participation, experts were instructed to use a second screen (either a tablet or smartphone) to scan a QR code, giving them access to Slido to answer the elicitation questions.
  Before starting the elicitation process, experts answered a calibration question. The purpose of this question was to ensure that all participants could properly configure and use their second screen for the study. Once this was confirmed, the elicitation team proceeded with the main study.
  The second part of the presentation was integrated with Slido to display the protocol questions and present the real-time analysis of the experts' responses. The elicitation questions were first presented in the PowerPoint slides. Simultaneously, the questions appeared on each expert's second screen, allowing them to answer in real time. After each answer was provided, Slido summarized them immediately and displayed the results for all participants to view the collective input.

If any ambiguities or clarifications arose from the analyzed data, the elicitation team prompted discussions to further explore the experts' reasoning. This approach facilitated a natural flow of expert insights, encouraging deeper and more useful input [40].

4. Results

This section presents the results of the two EEs studies. The first EE study covers feasibility, importance, widespread adoption, risk of delay in adoption, barriers to adoption, and open discussions. The second EE study includes the feasibility, importance, barriers to adoption, and open discussion. It concludes with a general discussion by integrating results obtained in the performance of the two EEs studies with existing literature.

4.1. First EE study

During the first elicitation study, experts joined and left the meeting at different times, leading to variability in the number of responses to each question. As a result, the number of experts who answered each question ranged from seven (7) to thirteen (13). To address this variability, we specify the number of experts who responded to each question in the results sections that follow.

4.1.1. Feasibility and importance - First EE study

This section presents the results of experts' perceptions on the feasibility and importance of DC solutions. A total of eleven (11) experts responded to questions about feasibility, and twelve (12) experts responded to questions about importance.

Regarding the feasibility of DC solutions, the majority of experts rated them positively. Specifically, nine (9) experts considered them *feasible*, while two (2) rated them as *very feasible*.

In terms of importance, experts generally perceived the DC solutions as important, with only one rating the smart and sustainable DC cables as *somewhat important* (see Fig. 1). During the discussion, two key concerns emerged. First, experts noted that the perceived importance of DC solutions varied depending on the demonstration area, such as ports, industry, buildings, and data centers. Second, it became apparent that some experts had not fully understood the concept of sustainability in DC cables. To address this, the elicitation team clarified that the smart and sustainable DC cables aim to have an optimal cable design that minimizes the use of environmentally friendly raw materials.

4.1.2. Time for widespread adoption - First EE study

In Fig. 2, experts' opinions on the expected time for the widespread adoption of each of the nine (9) DC solutions are presented. The number of responses varied between nine (9) and thirteen (13) for each DC solution. The presented results reflect the solutions with the highest number of responses.

Overall, six (6) out of the nine (9) DC solutions were rated as highly suitable for adoption before 2030. These solutions include the DC solution design tool, DC measurement device, DC-DC converters, protection DC system design tool, DC connectors, and LVAC–LVDC interlink converters.

One expert projected the adoption of the semiconductor-based circuit breaker by 2050. Meanwhile, the static protection system received three different answers with four (4) votes each: 2040, 2030, and before 2030. To better understand these outcomes, the elicitation team invited clarifications from the participants.

Participant $\mathbf{S_1E_3}$ commented: *"Maybe it needs to be clarified at the beginning of the presentation what exactly a static protection system is. I would suggest including an example that shows where, in the design process, this system or its methodology is applied"*.

Another concern related to the interpretation of "widespread" adoption. Participant $\mathbf{S_1E_7}$ noted: *"You have to take into consideration, what you consider 'widespread'. If it's for investment purposes, or for the general public"*. The elicitation team clarified that 'widespread' referred to adoption by the general public. This feedback was taken into account to improve the design of the second EE study protocol.

4.1.3. Risk of delay in adoption - First EE study

Risks of delay in the adoption of the nine (9) DC solutions were captured and are presented in Fig. 3. The number of responses per solution ranged from eleven (11) to nine (9).

A lower perception of risk (rated as insignificant) was observed for only three solutions: DC connectors, smart and sustainable DC cables, and protection DC system design tools. A moderate level of risk was identified for the DC measurement device and the DC solution design tool, with each receiving seven (7) moderate-risk ratings.

Conversely, a high level of concern (rated as critical risk) was recorded for several solutions. Seven (7) experts rated the DC connectors as posing a critical risk to adoption, while four (4) experts each assigned critical risk ratings to the smart and sustainable DC cables, DC-DC converters, and Low-Voltage Alternating Current (LVAC)-Low-Voltage Direct Current (LVDC) interlink converters.

The DC cables being rated as having an insignificant but also critical risk, the following discussion was raised by experts concerning the relationship between conductor materials used for the DC cables and its impact on the cost. $\mathbf{S_1E_7}$ highlighted that: *"I put it in the critical range, because we are in a big project here. Doing the electrification of the ports, though it's not in DC, but we have about seven kilometers of cable to put in, it's a giant cost"*. The concern was clarified by $\mathbf{S_1E_3}$, as: *"It is not only about the length of the cable in different applications or different installations. But, the point also is to check what is possible in terms of copper, or aluminum, because the cost will be higher according to the kind of conductor materials"*.

Experts explained that the perception of lower or higher risk was largely due to the availability of alternative solutions already on the market. They suggested that, as long as existing alternatives meet functional needs, stakeholders would be unlikely to prioritize adopting newer technologies.

However, Participant $\mathbf{S_1E_3}$ challenged this view, emphasizing that the innovations embedded within the proposed DC solutions, such as intertripping wires and the use of optimized, sustainable materials for the smart and sustainable DC cables, were not fully understood by the panel. Furthermore, Participant $\mathbf{S_1E_2}$ argued that the adoption of sustainable cables would be greatly accelerated if regulations mandating their use were established.

4.1.4. Barriers to adoption - First EE study

Eleven barriers were presented to the experts, who were asked to select the top five (5) barriers. All thirteen (13) participants responded, and the results are shown in Fig. 4. Due to space constraints in the figure, three barriers were shortened for presentation purposes:

- *Uncertain utility interaction: net metering, utility ownership, and agreed standards* was abbreviated as uncertain utility interaction.
- *Misconception and lack of knowledge leads to a lengthy/expensive design and permit process* was shortened to misconception and lack of knowledge in DC systems.
- *Public perceptions of DC and readiness to 'champion' installations from DC projects* was shortened to public perception of DC.

Ranking the barriers from most to least selected, the top barriers identified were: lack of sufficiently trained personnel, high costs of DC solutions, uncertain utility interaction, misconception and lack of knowledge in DC systems, and uncertain regulatory road-maps. These were followed by public perception of DC, lack of pilot projects, and concerns over power losses, quality, and safety. The lowest-ranked barriers were the lack of use cases where DC is advantageous, incompatibility of DC system components, and reduced reliability in DC devices.

During the discussion, the high ranking of the lack of trained personnel was highlighted. Participant $\mathbf{S_1E_{13}}$ noted: *"It's very interesting. It's very often disregarded in the literature, but in one of the first meetings we had for this project, this topic was raised even more than costs"*. Also,

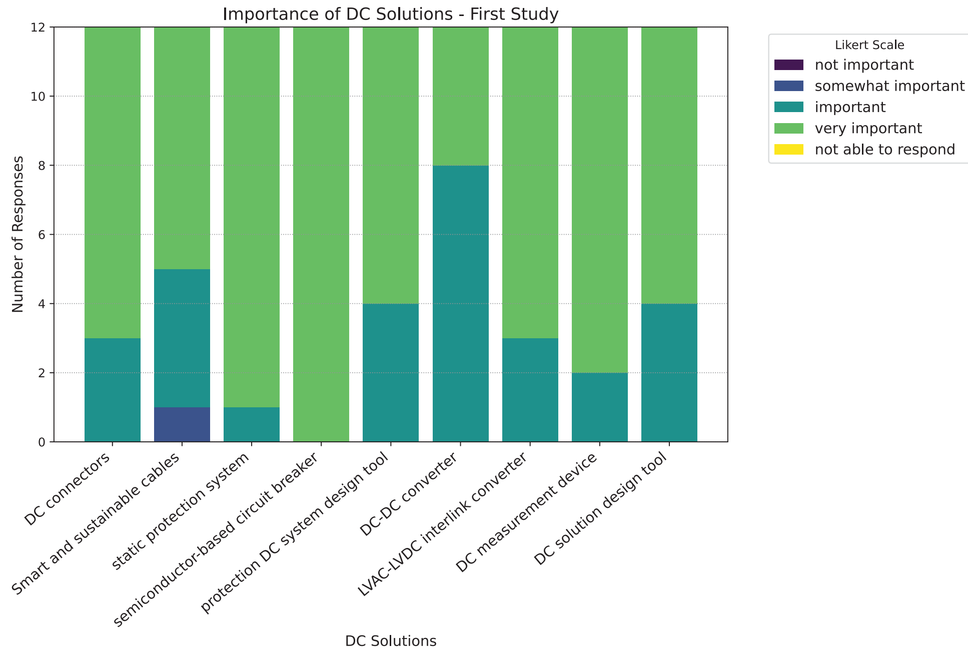

Fig. 1. Importance of each DC solution — First study.

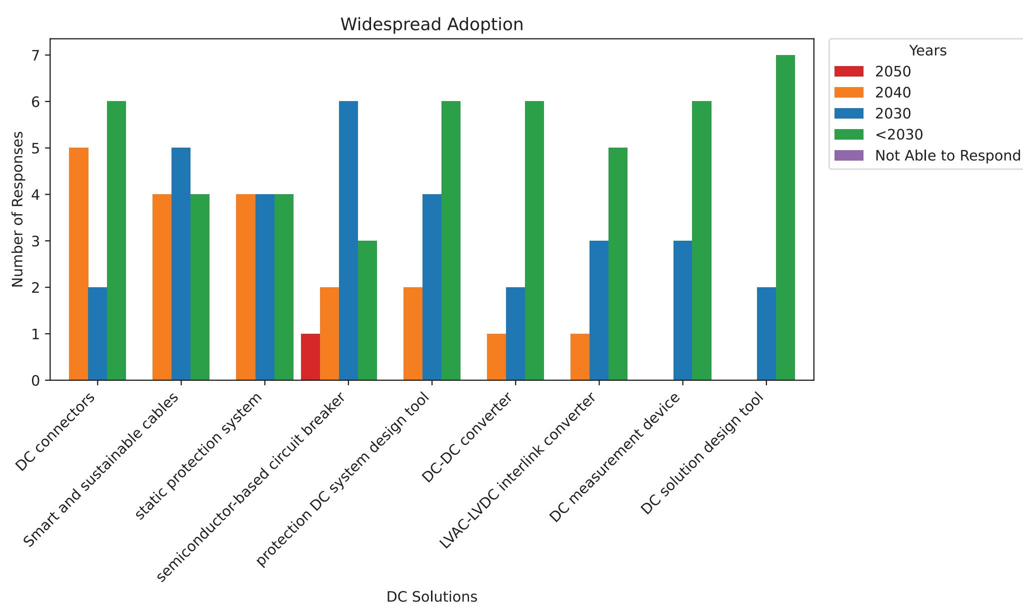

Fig. 2. Widespread adoption of DC solutions — First study.

added: *"I believe this result stems from the fact that we are experts; if we surveyed end users, the answers might differ significantly"*.

Regarding the high ranking of high costs of DC solutions, Participant $\mathbf{S_1E_5}$ explained: *"I chose high costs as a barrier because the adoption of DC technology will depend on early adopters building demonstration sites without full standardization. For that to happen, you need a viable cost–benefit analysis, but the current prices of DC products — still not produced at scale — hinder this"*.

Experts were also invited to suggest additional barriers. New barriers elicited from most to least perceived, included: lack of general public awareness, DC equipment interaction issues, lack of clear end-user advantages, unclear incentives, challenges with Total Cost of Ownership (TCO) comparisons, and the need for new technology.

On further inquiry about the "need for new technology", Participant $\mathbf{S_1E_6}$ explained: *"We're moving into new protection technologies based on power electronics. This shift away from decades-old solutions might cause hesitation among stakeholders"*.

Regarding the meaning of TCO comparison, Participant $\mathbf{S_1E_{10}}$ elaborated: *"TCO refers to comparing two solutions across a comprehensive scenario, covering not just installation costs but also operating costs and*

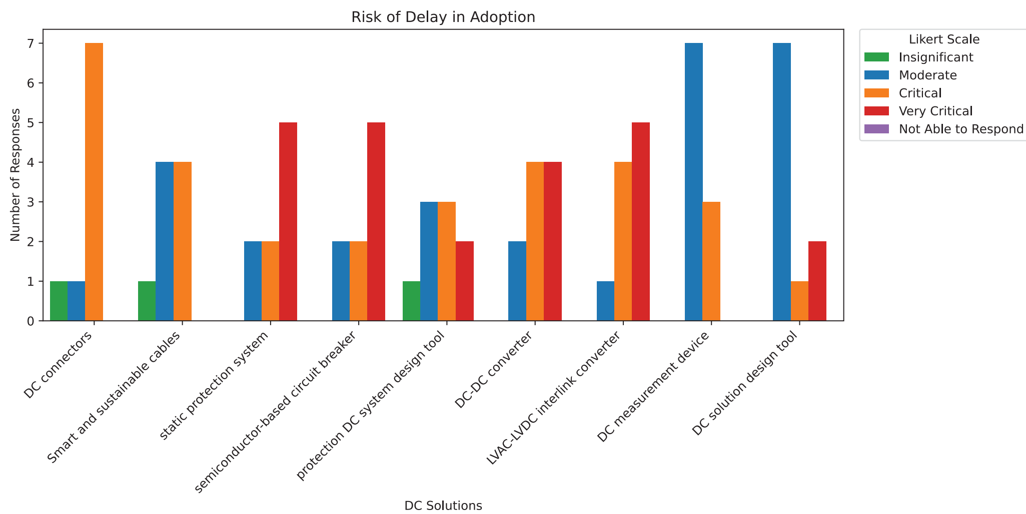

Fig. 3. Risk of delay in adoption of DC solutions — First study.

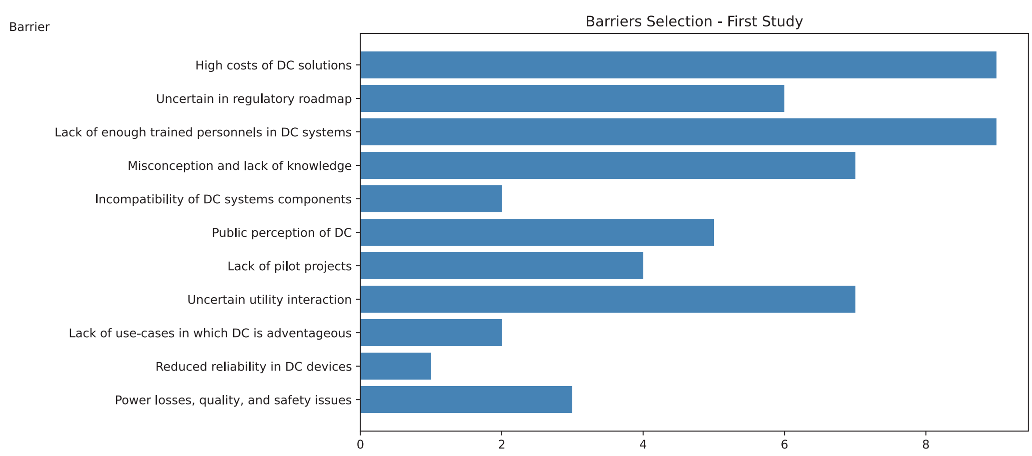

Fig. 4. Expert rating of barriers to DC adoption — First study.

other factors over a longer period". Participant $\mathbf{S_1E_3}$ agreed, adding: *"Users often compare technologies that are not at the same maturity level. The DC microgrid advantage should be compared against the AC grid standard, not against traditional AC installations only".*

Moreover, Participant $\mathbf{S_1E_4}$ shared a practical example illustrating the challenge of public understanding: in one project, although DC was technically suitable for a building, end-users did not perceive a clear advantage over conventional AC systems and therefore showed little interest.

Concerning the application of DC in demonstration projects, particularly in ports, Participant $\mathbf{S_1E_{13}}$ reflected: *"In some demos, it feels more obvious. For example, data centers clearly benefit from DC. But for ports, the roadmap is less clear. We're discussing onshore power supply while already introducing DC — it's like trying to leap before learning to walk".*

4.1.5. Open discussion - First EE study

During the open discussion, experts were invited to suggest any additional DC solutions they considered vital based on the targeted demonstrations.

Participant $\mathbf{S_1E_2}$ emphasized the importance of developing an Energy Management System (EMS) tailored specifically for DC applications, emphasizing that, while the development of individual devices is important, an interoperable EMS is crucial for ensuring the coordination and integration of different equipment. Establishing a common platform at the EMS level was seen as a key enabler for broader implementation of DC systems.

Building on this point, Participant $\mathbf{S_1E_{13}}$ highlighted related developments within the project, explaining, alongside efforts to create digital twins, the EMS has emerged as a particularly valuable tool, as it supports system management and interoperability across DC technologies. Also, added: *"We are also developing digital twins. But even beyond that, the EMS is something we already have within the project, and it's particularly interesting because it acts as one of the core tools enabling interoperability".*

4.2. Second EE study

This section presents the results from the second EE study. All eleven (11) experts participated throughout the session. The results cover three

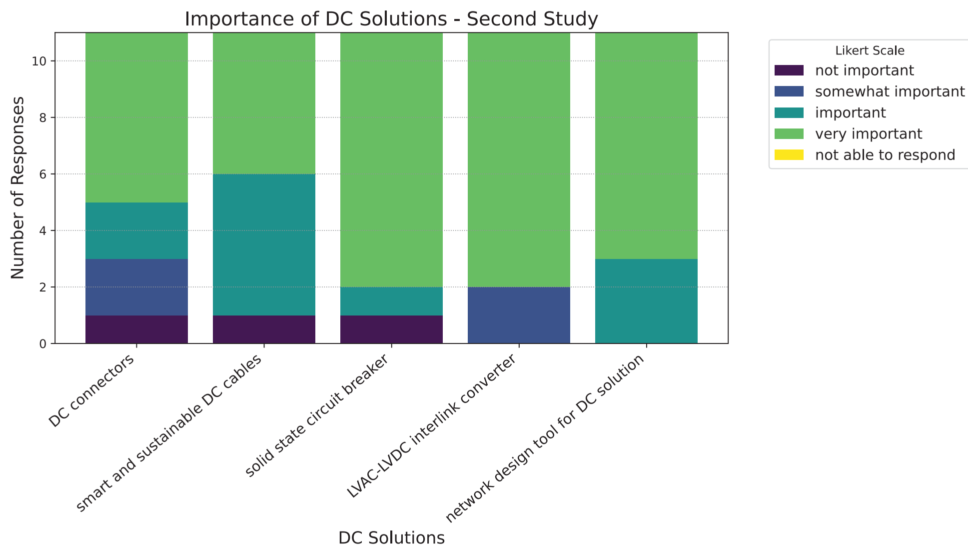

Fig. 5. Importance of DC solutions — Second study.

main areas: the assessment of importance and feasibility of the five (5) DC solutions, the barriers to their adoption, and the outcomes from the open discussion.

4.2.1. Feasibility and importance - Second EE study

As in the first study, this parameter aimed to gather experts' perspectives on the feasibility of the DC solutions. All experts perceived the DC solutions as feasible for the proposed project demonstrations. The ratings ranged between "feasible" and "very feasible", with seven (7) and four (4) votes, respectively. This mirrors the outcomes of the first elicitation study.

Following this, the elicitation team gathered expert insights on the importance of each DC solution. The results are summarized in Fig. 5, covering all five (5) solutions. For the smart and sustainable DC cables, five (5) participants rated them as "important", another five (5) as "very important", and one (1) as "not important". The elicitation team requested clarification regarding the "not important" rating. Participant $\mathbf{S_2E_8}$ explained: *"It's not that we don't need the DC cables to be smart. My point was that it's not essential. We need cables, but there are already cables, and we've found that you typically shouldn't need extra insulation with them. So, in some cases, you could use AC cables if you wanted to"*.

Regarding the DC connectors, six (6) experts rated as "very important", while one (1) rated them as "not important". Experts raised concerns that connectors have already been extensively researched, suggesting that existing solutions may suffice. They further noted that not all grid components are designed for plug-and-play installations. Participant $\mathbf{S_2E_2}$ elaborated: *"Not everything is pluggable. If you're doing an AC installation from the distribution cabinet, nothing is plugged. Depends on where you are"*. Explained, the necessity of DC connectors depends on the location within the grid.

For the solid-state circuit breaker, nine (9) experts rated as "very important", one (1) as "important", while one (1) rated it as "not important". Although no direct explanation was provided for the "not important" rating, participant $\mathbf{S_2E_6}$ emphasized the critical role of this DC solution: *"Actually, if we are thinking about interrupting currents in DC, it's a big deal. So, these devices must be important. We have to put some thinking when building them because they will be much harder to build than the other ones in AC"*.

Other DC solution experts rated the LVAC–LVDC interlink converter. Having nine (9) ratings as "very important", and two (2) as "somewhat important". Among the concerns raised is from participant $\mathbf{S_2E_3}$ explaining: *"That would not be the point is that we think as a Europeans. So we think of adding something to an existing AC network. It's linked with our existing electrical network"*. This was further elaborated, being concerned with the context of application in the DC grids. On the other hand, a concern on high voltage DC interlink was raised by Participant $\mathbf{S_2E_6}$ discussing: *"Maybe we should think about high voltage DC interlinks, because if we are thinking about maritime technologies, it's easy to have 10 megawatt. If you are talking about 400 V, the currents will exponentially increase. So high voltage will be something to consider"*. This was agreed by participant $\mathbf{S_2E_3}$ adding: *"Your point is relevant, though we are not talking about high voltage"*. The input was supported by other experts on the need to consider the future of port electrification separately, given the uncertainties related.

For the network design tool for DC solutions, eight (8) experts rated it as "very important", and three (3) as "important". Though the ratings were positive, the elicitation team sought insights from experts on this solution. Participant $\mathbf{S_2E_3}$ explained: *"It's much too complicated as there is a possibility to get different sources in the same network and so on. It seems very complicated to organize and to define a network without a software tool"*. This claim received agreement from participant $\mathbf{S_2E_7}$: *"The more the complicated microgrid, the more the simulation tools are required and second thing the robustness of the system also defines the optimization options that opens up for a second thing. It's a cost-sensitive matter on solutions' target countries and where they are developed"*. The elicitation team supported the contributions, explaining its alignment with the project.

4.2.2. Barriers to adoption - Second EE study

In this second study, twelve (12) barriers were presented for participants to vote on, with results shown in Fig. 6. Due to space limitations in the graph, three barriers were abbreviated as elaborated in Section 4.1.4.

The barriers are ranked from most to least selected based on expert responses. They were: lack of sufficient trained personnel in DC systems; uncertainty in the regulatory road-map; lack of use-cases demonstrating DC advantages; public perception of DC; readiness to

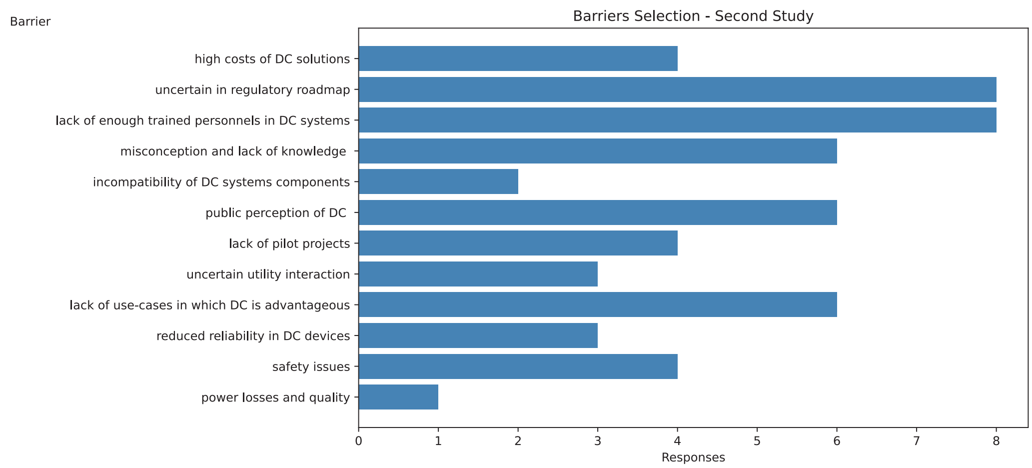

Fig. 6. Expert rating of barriers to DC adoption — Second study.

champion DC installations; misconceptions and lack of knowledge leading to costly design and permitting processes; lack of pilot projects; high costs of DC solutions; and safety issues. The least selected barriers were: reduced reliability of DC devices; uncertain utility interaction; incompatibility of DC system components; and power losses and quality issues.

High rating of lack of trained personnel also emerged as the most significant barrier, as findings from the first study (Section 4.1.4). The elicitation team explained the efforts to address incompatibility that are currently explored by Open Direct Current Alliance (ODCA) and Current-OS. They also inquired for insights from experts. Participant $\mathbf{S_2E_4}$ added: *"Though Current-OS and ODCA can certainly help, but we will need much more to have enough trained personnel in DC systems. The universities and different bodies that can deliver training services will need to contribute. So, ODCA and Current-OS can deliver a frame of courses or a book or a backbone or assets, and content, but probably not be capable to make and deliver those training services"*. The contribution was supported by participant $\mathbf{S_2E_1}$: *"We have the expertise, but we are not having training or certification bodies to provide that kind of training to skilled people or universities"*.

To deepen the discussion, participants were invited to suggest any additional barriers they considered critical but not previously listed. From most to the least cited additional barriers included: the lack of a DC grid code, high Capital Expenditure (CAPEX), limited test facilities for DC systems, regulatory gaps, resistance to change, inertia in mindset shifts, limited understanding of DC benefits by public authorities, robustness issues, and the aging of power converters. Fault protection in DC systems was emphasized separately under two labels: "DC fault protection" and "fault protection and mitigation". Investor preferences and interests were also identified as potential barriers.

Additionally, participant $\mathbf{S_2E_4}$ contributed: *"If the public does not support, and they cannot support if they don't understand, then the grid code has little chance of changing. I'm not sure that the utilities have the will to move forward, as they are AC companies by history. So, we need the support of the public authorities. We are already working at the European Commission on the set plan for DC technology"*.

On the other hand, participant $\mathbf{S_2E_1}$ explained: *"General unwillingness to change in our societies, DC is a different way than it has been done before. If a person is not willing to change, they will not even read a regulation"*. The participant also added: *"Like within the EU Fit for 55 or Green Deal initiatives, that puts a lot more emphasis on efficiency, and that is the driver, and then it was just the two different conferences were also DC was a highlight. These third industry players are the head of the regulatory or general public about the need to decarbonize, and energy efficiency is left at the center, and DC plays an important role"*. The discussion concluded by highlighting the necessity of securing strong support from public authorities, as the European Commission is already pursuing strategic efforts.

4.2.3. *Open discussion - Second EE study*

The open discussion in the second elicitation study raised several additional critical points.

One major topic was the urgent need to train personnel specifically for DC systems, particularly at the technician level, adding to what was already discussed in Section 4.2.2. Participant $\mathbf{S_2E_2}$ emphasized: *"We need education and don't think of engineers, we need technicians to train practical people"*.

Also, participant $\mathbf{S_2E_6}$ stressed on co-existence between AC and DC infrastructures rather than favoring one over the other. Quoted: *"At present, all the loads are AC mostly. So if we are thinking in a change from AC to DC, we should consider a point where they both coexist. Because if you want to change it directly, we have to always install something in the middle of what we have already and something that we should add extra exactly to put the things we already have working and that will be always an extra price"*.

In contrast to participant $\mathbf{S_2E_6}$ insights, participant $\mathbf{S_2E_2}$ argued: *"It's about installing loads of renewable including storage systems, electrolyzers, and the like, which are all DC systems. Connecting loads of DC to AC grids. It's not changing the AC grids"*. The participant added: *"Doing DC, you need to start from scratch because it's completely different, due to difference in physical principles"*. Interestingly, participant $\mathbf{S_2E_5}$ admitted: *"Completely agree, that is the biggest truth we heard today"*.

Experts were also invited to suggest additional DC solutions relevant to the project's planned demonstrations. Participant $\mathbf{S_2E_7}$ responded: *"All the technologies are already in place. We have only to bring awareness on the DC systems to the general public"*.

5. Discussion

This section provides a general discussion of the results obtained from the two EE studies, as presented in Sections 4.1 and 4.2. We interpret the findings from both studies in light of existing literature, focusing on six key concerns raised by the experts. These concerns include: the interoperability and standardization of DC solutions, the need for training experts in DC, and raising public awareness. Additionally, the co-existence of AC and DC systems, the positive perceptions regarding the current state of DC, and the alignment of barriers identified in our studies with those observed in different geographic regions are discussed.

DC interoperability, standards and regulations. As noted in Section 4.1.5, the lack of clear, universal standards for DC systems remains a significant barrier, affecting not only costs but also the interoperability of different systems and components. While industry efforts to standardize DC technologies are ongoing, the timeline for comprehensive standardization remains uncertain [2,41]. Moreover, experts expressed concerns about the need for regulations that would require the adoption and implementation of innovative DC technologies. For example, in the discussion on smart and sustainable cables, one participant pointed out that as long as no regulations are in place, stakeholders may be reluctant to embrace certain innovations, given the availability of alternative solutions on the market.

Trainings in DC systems. The necessity for technician-level training in DC systems was emphasized in Section 4.2.3. Experts highlighted that the transition from AC to DC technologies requires starting from scratch, even for those experienced with AC systems. Literature also underscores the importance of expert training [13]. The level of expertise required and the curriculum proposals put forward by experts in this study are vital for guiding policymakers and educational institutions in developing appropriate training programs for the future of DC.

General public awareness of DC solutions. The findings from this study highlight the critical need for public awareness about DC technologies and their advantages. Building familiarity and confidence among the general public is essential to support the successful deployment of DC systems. Experts agreed that any regulatory or infrastructural changes would face significant resistance without a well-informed and supportive public. This aligns with literature that stresses the need for behavioral change among energy users [42] and the current governmental energy management frameworks [43]. Also, policies and regulations for smart-grids technologies [44]. Additionally, experts suggested that public awareness, regulations implementation, and conformity would be crucial for the smooth implementation of pilot projects across the European Union (EU).

Two worlds that must co-exist. Several experts pointed out that while DC technologies and components are largely ready for deployment, successful implementation depends on bridging the gap between public and industry understanding. As noted in experts' contributions, AC and DC are based on distinct physical principles, making it essential for both systems to coexist rather than one replacing the other. This view is supported by existing literature, which acknowledges ongoing challenges in DC, such as the need for updated grid codes and the commercialization of DC technologies [45].

Positive evaluation of DC solutions. A deeper analysis of the barriers identified in the first and second elicitation studies reveals that concerns related to DC equipment or solutions, particularly the 'incompatibility of DC system components' and 'power losses and quality', received relatively low ratings. This suggests that industrial research and development efforts have significantly improved the efficiency and viability of DC solutions. Supporting this view, recent studies [46,47] have highlighted advancements in high-voltage DC (HVDC) systems for power transfer.

Barriers by geographic location. Literature indicates that expert opinions on various issues, such as research and development dynamics and costs associated with nuclear technologies, can differ based on geographic location, as seen in studies from the USA and EU [28]. Furthermore, a study conducted by Glasgo and colleagues warned of potential differences in expert perceptions based on location [13]. In our study, experts based in the EU rated the lack of trained personnel as one of the top barriers, echoing the results from Glasgo et al. (2018). Interestingly, this barrier has persisted over the past six years, with our EE studies conducted in 2024 and the Glasgo study in 2018. This suggests an ongoing need for authorities to focus on effective training strategies for DC experts, as discussed in Section 4.2.3.

6. Conclusion, lessons learned and future work

This section presents the three key closing parts of this paper: the conclusion drawn from the literature, methodology, and results of the two EE studies, lessons learned during the elicitation process, and suggestions for future work.

6.1. Conclusion

The increasing energy demand has driven the exploration of RES to meet growing needs while addressing the environmental and health risks associated with traditional energy production. The introduction of RES has opened up new avenues for involving multiple stakeholders in energy generation and distribution. However, as these systems typically generate DC power, they present new challenges for the energy sector, particularly as DC solutions are still in the early stages of development for MV and LV applications.

This paper aimed to explore experts' perspectives on eleven proposed MV and LV DC solutions within the Shift2DC project. Two group-based EE studies were conducted — one with experts within the project consortium and another with external experts. The group-based elicitation design facilitated rich discussions among experts, covering technical feasibility, the importance of the DC solutions, and the barriers to their adoption.

The results highlighted the need for structured educational programs at the technician level, emphasizing the importance of a specialized curriculum for DC systems. This education should extend to end-users, particularly in buildings where most consumers are directly impacted by the implementation of DC solutions. It is crucial to ensure these users are equipped with the knowledge necessary for the successful adoption of DC solutions. Furthermore, as end-users play an active role in decentralized energy systems such as microgrids and energy communities, aligning their perceptions early in the project's execution is essential for smooth integration.

In addition, there is a need for regulations to enforce the use of innovations in DC, since the availability of alternatives in the market has been highlighted to hinder their adoption. Additional concern in regulation on cost has been raised by experts as a pathway to early adopters' consideration of DC, also to the management of initial and operational expenses. On the other hand, a careful deliberation of introducing the innovations is vital to eliminate the challenge of pile-ups and increase the adaptability of innovations.

Ultimately, by capturing structured expert insights across domains such as ports, buildings, industry, and data centers, this study advances the state of the art and informs both research and policy in the EU, particularly on themes like interoperability, standards, training, and awareness that, despite being widely recognized, remain scarcely addressed in the literature.

6.2. Lessons learned

Several lessons were learned from this work, as presented below.

In the first study, participant numbers fluctuated, with experts joining and leaving the session at different times. This resulted in a participation range between 13 and 7. This lesson has two facets: first, it highlights the risk of divided attention or multitasking, a well-known methodological challenge in online research formats [48]. Second, it aligns with prior findings on the cognitive fatigue associated with lengthy elicitation processes, where the number of questions often exceeds experts' patience [16].

Consequently, the elicitation team must be prepared for this fluctuation. To mitigate this, the study protocol was reviewed, and adjustments were made for the second study to enhance its success. The improvements in the protocol were evident as the second study took only 90 min, 30 min less than the first study, as summarized in Table 1.

In the second study, a significant challenge was recruiting experts. Although 18 experts initially agreed to participate, only 11 could attend the scheduled session due to time constraints. This aligns with challenges highlighted in the literature, where experts often have time-intensive commitments [17], making it difficult for them to engage in additional tasks. Moreover, experts are difficult to recruit, particularly in emerging fields like DC technologies, where elicitation studies are still in early phases [17]. Furthermore, this is also a methodological challenge as online group-based EE requires synchronous participation (i.e, having all experts and the elicitation team attend and engage in real time) [49].

Interestingly, although the study did not explicitly consider cost as a factor, capital expenditure (CAPEX) emerged as a perceived barrier to the adoption of energy technologies in the second EE. While some studies have explored the costs of energy technologies in general [20, 30], others specifically address DC technologies [9,13]. This highlights the ongoing concern regarding the unsettled costs of DC technologies.

Another lesson learned relates to the limitations of the answer choices. In the first study, participant $\mathbf{S_1E_2}$ noted that the five-point scale used was restrictive, as their opinion often fell between two points. This feedback led to a discussion in the second study about possibly increasing the number of response options. However, due to the need to reduce the duration of the second study, this change was not implemented, but will be considered in future studies. One potential solution, as suggested in the literature, could be to use quantitative measures, such as probabilities, to capture a wider range of expert opinions [16].

In evaluating the relevance and effectiveness of the questions in the elicitation protocol, it was observed that questions regarding the widespread adoption of DC technologies rarely achieved consensus among experts. This is due to the numerous variables involved in assessing and clarifying experts' understanding. To improve the efficiency of the second study's protocol, it was decided to remove two sets of questions: one concerning widespread adoption and another regarding the risk of delay in adoption.

Finally, the first EE study raised concerns about the pile-up of innovative energy solutions. During discussions about the general public's understanding of DC technology, participant $\mathbf{S_1E_{13}}$ highlighted the challenge of adopting new technologies in ports, such as on-shore power supply. Although this concept is still not well understood, there is a strong push towards DC-focused electrification. This concern needs to be considered within a broader context, particularly from the users' perspective. Also development of policies, regulations, and educational strategies to ensure a seamless transition and smooth adoption by all involved stakeholders.

6.3. Future works

This section outlines the proposed extensions to this work, which are informed by both the results obtained and the challenges encountered during the execution of the EE methodology. These extensions aim to address gaps, enhance the elicitation process, and explore new directions that can contribute to advancing the adoption of DC solutions and improving expert elicitation practices for emerging technologies.

Table A.6
Expertise — First elicitation study.

S/No	Code	Expertise
1	S_1E1	DC power electronics
2	S_1E2	DC power electronics
3	S_1E3	DC power electronics
4	S_1E4	DC power electronics
5	S_1E5	Data Center electrification
6	S_1E6	DC protections
7	S_1E7	Ports electrification
8	S_1E8	DC power electronics
9	S_1E9	DC power electronics
10	S_1E10	Ports electrification
11	S_1E11	DC power electronics
12	S_1E12	DC protections
13	S_1E13	Academician

Table A.7
Expertise — Second elicitation study.

S/No	Code	Expertise
1	S_2E1	DC power electronics
2	S_2E2	DC interoperability
3	S_2E3	DC power electronics
4	S_2E4	Buildings electrification
5	S_2E5	Academician
6	S_2E6	Academician
7	S_2E7	DC power electronics
8	S_2E8	DC power electronics
9	S_2E9	Academician
10	S_2E10	DC power electronics
11	S_2E11	AC/DC power systems

Experts sensitizing. While briefings on the studied DC solutions were provided in both elicitation studies, a recurring issue was the lack of sufficient clarity — as literature highlights when wording qualitative elicitation questions [16]. In particular, experts struggled to fully comprehend the innovative features of technologies like the smart and sustainable DC cables, as observed in the second elicitation study. This challenge suggests a need for more detailed and clear explanations in the briefing materials. Experts' difficulty in grasping the full scope of innovation highlights the importance of refining how these technologies are communicated. Future studies should implement a strategy to ensure that all experts have a thorough understanding of the technology before the elicitation process, possibly through pre-study workshops or more interactive and in-depth briefing sessions.

Experts sampling. In the design of expert elicitation studies, it is essential to consider a mix of expertise, as outlined by Knol et al. [22], who recommend a blend of normative experts, generalists, and subject-matter experts. However, our studies primarily relied on expert availability, as is common in many elicitation studies (e.g., Machado et al. [20]; Shayegh et al. [32]). This approach led to an imbalance in the types of expertise represented in the studies, as seen in the demographic breakdown in Tables A.6 and A.7. For future elicitation studies, it is recommended to adopt a more systematic sampling strategy that ensures a diverse representation of expertise across different domains. This will help to gather a more comprehensive range of perspectives and improve the robustness of the elicitation process.

Emerging technologies for EE studies. Given the challenges encountered in conducting these two elicitation studies, such as expert availability and the time constraints they face, future work will explore the integration of emerging Information and Communication Technologies (ICT) tools. Recent advancements in ICT have the potential to transform the expert elicitation process by providing more flexible, real-time platforms for collaboration and feedback. By leveraging virtual environments, machine learning algorithms, or other digital tools, we can streamline the elicitation process, minimize participant fatigue, and enhance the overall efficiency of expert studies. This shift could

Table B.8
Descriptions of DC solutions.

S/No	DC solution	Description
1	Smart and sustainable DC cables	Cables to provide the interface between DC sources and loads, conforms Current-OS specifications, consider aspects such as "electrothermal aging", ergonomics, and environmental impact.
2	DC connectors	DC connectors manage safe connection and disconnection in DC grids, using active or passive arc extinguishing methods to prevent damage and ensure user safety.
3	Static protection system	Provides ultra-fast protection for DC microgrids, quickly isolating faults and ensuring system reliability using advanced detection and solid-state breakers.
4	Semiconductor-based circuit breaker	A solid-state circuit breaker to quickly and reliably protect DC grids, overcoming the challenge of no natural zero-crossing in DC currents.
5	Protection DC system design tool	Enable the design of protection system for DC grids.
6	DC–DC converter	Power-flow-control between DC appliances.
7	LVAC–LVDC interlink converter	Active-front-end with droop-control capabilities on the DC side.
8	DC measurement device	Current measurements up to 1000 A DC, Voltage measurement up to 1500 V DC.
9	DC solution design tool	Evaluate different DC architectures and compare with conventional AC radial networks.
10	Network design tool for DC solutions	Integrates static models of some specific DC devices, Supports different DC eco-systems.
11	Solid-state circuit breaker	Real-time monitoring and communication capabilities, adaptive protection scheme, adjusting to varying grid conditions.

reduce the burden on experts, allowing them to participate more readily and provide more thoughtful and comprehensive responses. We envision the future integration of these technologies to improve the quality, scalability, and accessibility of EE in early-phase fields like DC solutions.

CRediT authorship contribution statement

Catherine Ngirwa: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Diogo Reis:** Writing – review & editing, Software, Resources, Methodology, Investigation, Data curation. **Hugo Morais:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition. **Lucas Pereira:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

While conducting the EE studies, the Read.AI was used for recording and transcription. After using this tool, the authors reviewed the transcripts and edited them for understanding with the aid of the recordings. We, the authors, take full responsibility for the content of the published article.

Declaration of competing interest

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

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Appendix A. Expertise per expert

See Tables A.6 and A.7.

Appendix B. The DC solutions

See Table B.8.

Appendix C. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.erss.2025.104370.

Data availability

Data will be made available on request.

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