Financial Models and Incentives for Clean Energy Investment

D I S S E R T A T I O N
of the University of St.Gallen,
School of Management,
Economics, Law, Social Sciences,
International Affairs and Computer Sciences,
to obtain the title of
Doctor of Philosophy in
International Affairs and Political Economy

submitted by

Elizabeth Côté

from

Canada

Approved on the application of

Prof. Dr. Rolf Wüstenhagen

and

Dr. Geraldine Ryan

Dissertation no. 5271

Difo-Druck GmbH, Untersiemau 2023

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The University of St.Gallen, School of Management, Economics, Law, Social Sciences, International Affairs and Computer Science, hereby consents to the printing of the present dissertation, without hereby expressing any opinion on the views herein expressed.

St. Gallen, October 21, 2022

The President:

Prof. Dr. Bernhard Ehrenzeller

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List of abbreviations and symbols[1]

ACA	Adaptive conjoint analysis
ACBC	Adaptive choice-based conjoint analysis
AIS	Average importance score
Avg.	Average
CAES	Compressed air energy storage
CBC	Choice-based conjoint analysis
CEC	Community energy company
CHF	Swiss franc
CI	Confidence interval
CO_2	Carbon dioxide
COVID-19	Coronavirus disease
Ct	Cent
DCE	Discrete choice experiment
ESS	Energy storage system
EU	European Union
GHG	Greenhouse gases
GW	Gigawatt
HB	Hierarchical Bayes
HP	Heat pump
IRR	Internal rate of return
kg	Kilogram
km	Kilometre

[1] Abbreviations and symbols are introduced in each relevant chapter.

kW	Kilowatt
kWh	Kilowatt-hour
Li	Lithium-ion
m^2	Square meter
Min	Minute
MW	Megawatt
MW_e	Megawatt of electricity input
MWh	Megawatt hour
No.	Number
No. of resp.	Number of respondents
PEM	Polymer electrolyte membrane
PHS	Pumped hydro storage
PPA	Power purchase agreement
PV	Photovoltaic
RE	Renewable energy
RES	Renewable energy source
Resp. rate	Response rate
RLH	Root likelihood
SD	Standard deviation
SME	Small and medium-sized enterprise
USD	United States dollar
WTA	Willingness to accept
WTP	Willingness to pay
€	Euro

Abstract

Achieving net zero by 2050 requires considerable investment to scale up clean energy generation capacity, expand and modernise power networks, and electrify end-users. However, clean energy projects are facing growing opposition. While several policy makers have introduced measures aimed at incentivizing citizen co-ownership to foster acceptance, little is understood about how these measures influence investment decisions. Further, clean energy business models are often found to be unprofitable, and financial factors may hinder the diffusion of key technologies. This has prompted several actors to call for policy support and business model innovation.

With this dissertation, I contribute to a better understanding of how the attributes of energy policies and business models influence investors' risk perceptions and return expectations. This enables me to identify financial mechanisms, business models, and incentives that may promote investment. Three critical challenges pertaining to clean energy investment are considered, each addressed in a standalone research paper.

In *Paper 1*, we investigate how auction design elements aimed at fostering citizen participation influence project developers' risk perceptions and bidding decisions. We show that increasing actor diversity comes at a cost, and that policy makers unwilling to compensate developers will have to find other ways to promote participation, as this could have important implications for renewable energy investment.

In *Paper 2*, we examine the preferences of institutional investors and utility companies for energy storage investment. We find that both investor groups have a strong aversion to non-regulated forms of revenue. We also show that hedging their exposure to electricity price risk – at least partly – through policy incentives or corporate power purchase agreements could decrease financing costs and promote investment.

In *Paper 3*, I investigate homeowners' preferences for heat-pump leasing. I show that flexible, all-inclusive leasing offerings could contribute to decarbonizing residential heat, especially in markets where heat pumps are at an early stage of diffusion like in Germany. Policy makers who wish to promote heat-pump diffusion may consider adapting incentives to account for these service-based offerings.

Zusammenfassung

Um bis 2050 null Nettoemissionen zu erreichen, sind beträchtliche Investitionen erforderlich, um die Kapazitäten zur nachhaltigen Energieerzeugung zu erhöhen, die Stromnetze auszubauen und zu modernisieren, und die Elektrifizierung voranzutreiben. Saubere Energieprojekte stossen jedoch auf wachsenden Widerstand. Zwar haben politische Entscheidungsträger Massnahmen eingeführt, die Anreize für Bürgerbeteiligung zur Förderung der Akzeptanz schaffen sollen, es ist jedoch wenig darüber bekannt, wie diese Massnahmen Investitionsentscheidungen beeinflussen. Ausserdem erweisen sich Geschäftsmodelle für saubere Energien oft als unrentabel, und finanzielle Faktoren können die Verbreitung von Schlüsseltechnologien behindern. Dies hat mehrere Akteure dazu veranlasst, politische Unterstützung und innovative Geschäftsmodelle zu fordern.

Mit dieser Dissertation trage ich dazu bei, besser zu verstehen, wie Eigenschaften von energiepolitischen Regeln und Geschäftsmodellen die Risikowahrnehmung und die Renditeerwartungen von Investoren beeinflussen. Dies ermöglicht es mir, Finanzmechanismen, Geschäftsmodelle und Anreize zu identifizieren, die Investitionen fördern können. Es werden drei entscheidende Herausforderungen im Zusammenhang mit Investitionen in nachhaltige Energie betrachtet, die jeweils in einem eigenständigen Forschungsartikel behandelt werden.

In *Artikel 1* untersuchen wir, wie Elemente von Auktionen, die auf die Förderung von Bürgerbeteiligung abzielen, die Risikowahrnehmung der Projektentwickler und Gebotsentscheidungen beeinflussen. Wir zeigen, dass die Erhöhung der Akteursvielfalt mit Kosten verbunden ist und wenn politische Entscheidungsträger nicht bereit sind Projektentwickler zu entschädigen, dann müssen diese andere Wege finden, um die Beteiligung zu fördern, da diese wichtige Auswirkungen auf Investitionen in erneuerbare Energien haben könnte.

In *Artikel 2* untersuchen wir die Präferenzen von institutionellen Investoren und Versorgungsunternehmen für Investitionen in Energiespeicher. Wir stellen fest, dass beide Investorengruppen eine starke Abneigung gegen nicht-regulierte Formen von Einnahmen haben. Wir zeigen auch, dass die Absicherung ihres Strompreisrisikos durch politische Anreize oder Stromabnahmeverträge – zumindest teilweise – die Finanzierungskosten für Unternehmen senken und Investitionen fördern könnte.

In *Artikel 3* untersuche ich die Präferenzen von Hausbesitzern beim Leasing von Wärmepumpen. Ich zeige, dass flexible, allumfassende Leasingangebote zur Dekarbonisierung der Wärmeversorgung von Haushalten beitragen könnten, insbesondere in Märkten wie Deutschland, in denen sich Wärmepumpen noch in einem frühen Stadium der Verbreitung befinden. Politische Entscheidungsträger, die die Verbreitung von Wärmepumpen fördern wollen, sollten daher Anreize anpassen, um diese dienstleistungsbasierten Angebote zu fördern.

Introductory Chapter

1. Background and research motivation

Growing concerns over the effects anthropogenic greenhouse gases (GHG) emissions have on the climate have prompted governments in more than 137 countries to commit to reducing emissions to net zero by mid-century (Wallach, 2021). This pledge is in line with the Paris Agreement objective of limiting the rise in global temperature to "well below 2°C" compared to pre-industrial levels, and most preferably, to a maximum 1.5°C increase (UN, 2020). Given that 73.2% of global GHG emissions are generated within the energy sector, tackling its decarbonisation through the large-scale deployment of clean energy technologies has become a high priority on the agenda of policy makers (Ritchie, 2020). Achieving net zero could require up to USD 173 trillion in clean energy investment by 2050 (BloombergNEF, 2021).[2] Most of this expenditure is required to: 1) scale up clean electricity generation capacity, 2) expand and modernise power networks, and 3) electrify end-users (IEA, 2021).

First, electricity could account for 49% of final energy consumption by 2050 in a net-zero economy, a steep increase from the 19% observed today (BloombergNEF, 2021). To meet this demand, annual investment in power generation capacity needs to increase from USD 500 billion per year to over USD 1,600 billion in 2030 (IEA, 2021). A considerable share of this capital is needed to scale up electricity generation from variable renewable energy sources – namely, wind and solar energy, which could provide up to 84% of the global electricity supply by 2050 (BloombergNEF, 2021).[3] However, renewable energy projects are facing growing opposition (Brindley and Fraile, 2021; MTES, 2018). While policy makers in several countries have recently introduced provisions within renewable energy auction schemes to incentivize the participation of citizens in projects to foster their acceptance, little is understood about how these measures influence developers' investment decisions.

[2] This entails global annual investment increasing from USD 1.7 trillion per year to an average of up to USD 5.8 trillion per year over the next three decades (BloombergNEF, 2021).

[3] BloombergNEF (2021) proposes three pathways to net zero. In the Red Scenario, power generation comes from nuclear (56%), wind (27%), and solar (12%) energy. In the Gray Scenario, it comes from wind energy (40%), natural gas and coal with carbon capture and storage (24%), and solar energy (22%). In the Green Scenario, variable renewable energy sources dominate – i.e., 52% wind and 32% solar energy (BloombergNEF, 2021).

Second, the growing share of intermittent energy sources affects the quality, flow, stability, and balance of power systems (Sinsel et al., 2020). To ensure grid reliability, investment in network expansion and modernisation need to increase from USD 260 billion per year today to nearly USD 800 billion in 2030 (IEA, 2021). A substantial share of this expenditure is required to deploy energy storage, most notably grid-scale battery storage and hydrogen production and storage (BloombergNEF, 2021; Capros et al., 2019). However, business models are often found to be unprofitable or complex (Baumgarte et al., 2020). While this has prompted several scholars and industry actors to call for policies to mitigate risks for investors (BloombergNEF, 2020; Martins and Miles, 2021; Nikolaidis and Poullikkas, 2017; Vorushylo et al., 2016), little is known about what kind of support could promote energy storage investment.

Third, beyond power generation and storage, substantial investment in electric equipment is also required to electrify end-users. Heat pumps[4] represent a promising solution, thanks to their high efficiency and flexibility (Brockway and Delforge, 2018; Howden-Chapman et al., 2009). To reach net zero, 186 million households would need to replace their fossil-fuel-fired heating systems with heat pumps by 2030, and 1.4 billion by 2050 (BloombergNEF, 2021). However, financial factors such as high investment costs often hinder adoption (Gaur et al., 2021; Mahapatra and Gustavsson, 2008; Michelsen and Madlener, 2016). While asset leasing – whereby a service provider leases an appliance and provides services to an end-user in exchange for monthly payments – could address some of the barriers faced by homeowners in the adoption of heat pumps, little is known about their preferences for such services.

This doctoral dissertation considers three critical challenges, each addressed sequentially in the subsequent chapters. First, since measures aimed at incentivizing citizen participation in renewable energy projects subject to auctions may influence developers' risk perceptions, there is a need to determine how these measures impact investors' return expectations and bidding decisions. Second, while policies could play an important role in rendering energy storage economically viable, there is a need to clarify what kind of support could promote investment. Third, as asset leasing could contribute to enabling heat-pump diffusion, there is a need to elucidate homeowners' preferences for different service offerings.

[4] Devices that transfer thermal energy between spaces using electricity – e.g., from external heat sources such as air or water to heat that can be used for space heating and/or hot water supply.

1.1. Overall research aim and research foci

Against this background, this cumulative dissertation aims at shedding light on the preferences of investors for clean energy investment. It also quantifies their willingness to accept (WTA) risk and willingness to pay (WTP) for services. Obtaining a better understanding of risk perceptions and return expectations enables me to uncover financial mechanisms, business models, and incentives that may promote investment. The following overarching research question is formulated to achieve this aim:

How do the attributes of clean energy policies and business models influence investors' risk perceptions and return expectations?

I address this question by drawing empirical insight from investors using a sequential exploratory mixed-method design featuring three choice experiments (see Section 3). This approach enables me to obtain a better understanding of the dynamics between specific investment features, policies, and investment decisions. The focus is on project developers, utility companies, institutional investors, and homeowners.[5] This set of investors is interesting, as they exhibit contrasting motivations, resources, and experience (Bergek et al., 2013; McInerney and Bunn, 2019) – see Subsection 3.2 for details. Since they invest in different project phases or innovation stages, they are key complementary actors in the clean energy investment ecosystem. Further, this research endeavour focuses on investment in clean power generation, energy storage, and electric equipment, as these technologies are expected to play a key role in achieving net zero.

This dissertation is particularly relevant for investors and policy makers who wish to promote clean energy investment. Obtaining a better understanding of how provisions aimed at incentivizing citizen participation influence developers' risk perceptions allows me to derive recommendations that may help policy makers to find the right balance between cost-reducing and risk-increasing auctions. Shedding light on the preferences of investors for energy storage investment also enables me to define actor-specific policy implications. Finally, service providers may benefit from insights into homeowners' preferences for heating services to design offerings that meet their needs.

[5] Project developers are privately owned firms active in the planning, building, commissioning, and initial operation of clean energy assets (Bergek et al., 2013). Utility companies are the state- and/or privately-owned firms who provide commodities to consumers. They are strategic investors who are mostly concerned with power generation, transmission, and storage. Institutional investors are profit-oriented entities who pool capital from their clients to purchase securities, real property, assets, or to make loans (IRENA, 2020a). Homeowners are natural persons who own residential infrastructure.

1.2. Structure of the dissertation

The remainder of this dissertation is structured as follow: Section 2 of the present chapter provides an overview of the three research papers that constitute the core of this work. Section 3 defines the theoretical foundations and presents the conceptual framework that ties the papers together. Section 4 elaborates on the methodological design. Section 5 summarizes the main findings, discusses their implications, and suggests future lines of research. The papers are addressed in the subsequent chapters.

2. Focus and objectives of the research papers

This dissertation comprises three standalone research papers, each addressing a challenge pertaining to clean energy investment, as specified in Section 1. Côté et al. (2022) (hereafter *Paper 1*) examines developers' risk perceptions in the context of auctions. Côté and Salm (2022) (hereafter *Paper 2*) investigates investors' preferences for energy storage investment. Côté (2022) (hereafter *Paper 3*) examines homeowners' preferences for heat-pump leasing. Table 1 provides an overview of the research papers.

In *Paper 1*, we investigate how auction design elements aimed at fostering citizen participation influence project developers' risk perceptions and bidding decisions. Scholars have shown that citizen participation plays a determining role in enhancing the acceptance of renewable energy projects (Bauwens and Devine-Wright, 2018; Vuichard et al., 2019), including financial participation through co-ownership[6] (Musall and Kuik, 2011). While several governments have introduced measures to incentivise citizen co-investment[6] in projects subject to auction-allocated support, auction results suggest a limited understanding of developers' risk perceptions (Rüdinger, 2019). We address this issue by drawing insights from 559 experimental bidding decisions made by 61 European onshore wind energy project developers. We find that developers are generally open to co-investment. However, they would on average demand 1.3 percentage points in compensation to bid in an auction at which 20% of project equity is required to be open to citizen co-investment compared to a setting where no co-investment is required. These insights highlight the apparent trade-off between

[6] Renewable energy assets jointly owned by a professional developer and local citizens through, for example, a co-investment schemes (e.g., local citizens invest equity capital and own shares of the project, with voting rights). The terms co-investment and co-ownership are used interchangeably in *Paper 1*.

promoting actor diversity and low-cost energy generation. Policy makers unwilling to compensate developers for the price of increasing actor diversity will have to find other ways to promote citizen participation, as this could have important implications for investment in clean power generation capacity.

In *Paper 2*, we examine the preferences of institutional investors and utility companies for energy storage investment. While storage could play an important role in future energy systems (Blanco and Faaij, 2018; Victoria et al., 2019), investments in less mature technologies are often unprofitable and complex (Baumgarte et al., 2020). Since private investors could play an important role in financing such assets (Huang et al., 2020), there is a need to obtain a better understanding of their risk-return requirements with a view to mobilizing their full investment potential. We address this gap by gaining insight from 1,605 experimental investment decisions made by 42 institutional investors and utility company representatives. Our findings underline the important role policies could play in mitigating energy price risk for investors. Institutional investors would require an average premium of 6.87 percentage points and utilities 5.54 percentage points to move from a position of being fully hedged against market price risk to a scenario whereby only 20% of revenues are fixed. Since both groups have a strong aversion to non-regulated revenue streams, finding ways to hedge the exposure to electricity price risk of these investors – at least partly – could decrease financing costs and promote investment.

In *Paper 3*, I investigate homeowners' preferences for heat-pump leasing. I also quantify their WTP for different heating services and examine their inclination to lease or purchase a heat pump. Several barriers to heat-pump adoption exist (see Section 1), and service-based offerings such as asset leasing could help overcome these challenges by, notably, eliminating upfront investment requirements (Britton et al., 2021; Brown et al., 2022). However, little is known about homeowners' preferences for heating services (Schleich et al., 2021; Sovacool et al., 2021). I address this issue by drawing insight from 915 single-family homeowners who undertook 9,150 hypothetical heat-pump-leasing-related decisions in France, Germany, and Switzerland. Survey results show that flexible, all-inclusive leasing offerings could contribute to decarbonizing heat, especially in markets where heat pumps are at an early stage of diffusion. German homeowners are the most open to leasing and would on average pay up to three times more than their French counterparts to shield themselves against technical risk. Given the role service-based offerings could play in decarbonizing heat, policy makers may wish to adapt incentives to account for these offerings.

Table 1: Overview of the dissertation research papers.

Paper No.	Title	Author(s)	Research objectives	Methods	Expected academic contribution	Publication status
1	The price of actor diversity: Measuring project developers' willingness to accept risks in renewable energy auctions	Elizabeth Côté[a] Mak Đukan[b] Cristian Pons-Seres de Brauwer[c] Rolf Wüstenhagen[a]	Investigate the risk perceptions of developers for various auction design features and shed light on their preferences for different forms of citizen participation. Provide policy recommendations.	Semi-structured interviews Choice-based conjoint analysis	Renewable energy auction, citizen participation, project developers' decision-making, and energy policy literature	Published in *Energy Policy*
2	Risk-adjusted preferences of utility companies and institutional investors for battery storage and green hydrogen investment	Elizabeth Côté[a] Sarah Salm[d]	Quantify utility companies and institutional investors' WTA risk related to energy storage investment. Provide guidance for the design of investor-specific policies.	Semi-structured interviews Adaptive choice-based conjoint analysis	Energy storage, professional investors' decision-making, and energy policy literature	Published in *Energy Policy*
3	Preferences of homeowners for heat-pump leasing: Evidence from a choice experiment in France, Germany, and Switzerland	Elizabeth Côté[a]	Investigate the preferences of homeowners for leasing offerings, examine their inclination to lease or purchase, and quantify their WTP for services. Inform service providers and policy makers about best practices for designing leasing offerings and related policy measures.	Transdisciplinary approach Choice-based conjoint analysis	Service-based business model for low-carbon heating, homeowners' decision-making, and energy policy literature	Submitted to *Energy Policy*

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3. Theoretical foundations and conceptual framework

In this section, I first review the financial mechanisms and business models that emerged from the decentralization and servitization of business activities in the energy sector. In doing so, I draw on several research streams – notably, social acceptance, energy storage, and service-based business model research. Second, I review research on strategic investment decision-making to obtain a better understanding of how risk perceptions and return expectations may vary between different types of investors. Third, I provide a theoretical perspective on the role public policies play in mitigating investment risk and shaping business models. Fourth, I present the conceptual framework that links the three papers together.

3.1. Financing mechanisms and business models in the energy transition

Decarbonization efforts have led to two paradigm shifts in the energy sector: the decentralization and servitization of business activities (Frei et al., 2018). Decentralization implies a shift from large-scale, centralized power generation to smaller, distributed electricity production. Servitization is a form of business model innovation or value creation whereby end-users pay for the services they obtain from a product rather than for a product *per se* (Singh et al., 2022). These two transformative trends prompted the emergence of new financial mechanisms and business models for clean energy assets, of which three are presented in the following subsections.

3.1.1. Co-ownership and social acceptance of distributed power generation

First, with the decentralization and proliferation of distributed power generation facilities, new renewable energy projects are increasingly met with opposition. This has led to growing recognition of the decisive role social acceptance plays in the achievement of climate goals (Wüstenhagen et al., 2007). Social acceptance research has shown that citizen participation in projects can foster acceptance (Bauwens and Devine-Wright, 2018; De Luca et al., 2020; Vuichard et al., 2019), including financial participation (Johansen and Emborg, 2018; Lienhoop, 2018). A variety of financing models that include some form of financial participation by citizens or communities exist (Mignon and Rüdinger, 2016; Slee, 2015; Yildiz, 2014). However, the effect

specific models have on acceptance is sometimes unclear (Rüdinger, 2019). Prior studies have revealed that community ownership and the participation of local actors are predictors of acceptance (Walker and Devine-Wright, 2008; Warren and McFadyen, 2010). While some scholars have shown that co-ownership by professional developers and local citizens enhances acceptance (Musall and Kuik, 2011), others argue that challenges associated with implementing such models can undermine acceptance (Goedkoop and Devine-Wright, 2016). Co-ownership can also result in additional risks and costs for developers (Brindley and Fraile, 2021; Quentin, 2019). Despite these challenges, policy makers in several countries have introduced measures to incentivize citizen co-ownership. However, empirical evidence about how these measures affect developers' risk perceptions is scarce.

3.1.2. Energy storage business models in decentralized power systems

Second, the decarbonization and decentralization of power systems is challenging grid infrastructure (Ajaz and Bernell, 2021). Although renewable energy sources provide several benefits, they are also associated with challenges such as unsynchronized output, uncertain resource availability, and spatial constraints (Sinsel et al., 2020). Energy storage offers a promising solution for integrating the growing shares of variable renewable energy sources into power systems (Arbabzadeh et al., 2019; Blanco and Faaij, 2018). While the extent of their role in future systems is subject to scholarly debate (Jurasz et al., 2020),[7] there appears to be some consensus about their relevance for abating the final shares of carbon emissions (Victoria et al., 2019). Specifically, storage could play a key role in addressing the seasonal mismatch between renewable power generation and demand (Petkov and Gabrielli, 2020). It may also help provide other critical services like ancillary services and peak shaving (see *Paper 2* for details on energy storage business models).

Given the versatility of battery storage and potential role that hydrogen could play in ensuring seasonal storage, some scholars regard these technologies as key components of future energy systems (Capros et al., 2019; Moore and Shabani, 2016; Sani et al., 2020). However, research has shown that energy storage business models are often

[7] For example, the hybridization of power stations through the inclusion of multiple renewable energy sources such as wind, solar and/or hydropower can lessen the need for energy storage due to complementarity in power generation profiles. However, some technologies may face acceptance issues that could challenge the deployment of hybrid solutions.

unprofitable or complex (Baumgarte et al., 2020), as they may require stacking several revenue streams (Farag et al., 2020; Lombardi and Schwabe, 2017; Martins and Miles, 2021). While scholars have highlighted the need for policy support to mitigate risks for investors (Nikolaidis and Poullikkas, 2017; Vorushylo et al., 2016), little is known about what kind of support may prompt investment in these key technologies.

3.1.3. Service-based business models for low-carbon heating

Third, the servitization of business activities could arguably be the result of several developments; notably: 1) decentralization enables a growing share of renewable energy to be produced by end-users; and 2) broadening incentives creates new opportunities for companies to support end-users in the adoption of climate solutions (Frei et al., 2018). A growing stream of research in the field of energy economics investigates servitization, with studies dealing with different applications, stakeholders, and geographical scopes (Britton et al., 2021; Helms, 2016; Singh et al., 2022, 2021). A variety of service-base business models exist (Brown et al., 2022; Chasin et al., 2020; Fell, 2017). The latter can be understood as offerings in which financial, technical, performance, behavioural, and energy price risks are all or in-part borne by service providers (Delta-EE, 2019). Offerings bundle several activities, and revenue streams can emerge from the margins made on equipment installation, financing, and subscription-based contracts (IRENA, 2020b; Park, 2022).

In particular, asset leasing has emerged as a solution for supporting households in the adoption of climate solutions. Scholars have shown that this model can facilitate the adoption of residential solar photovoltaic (PV) by new market segments, who are often characterised by younger, less affluent, and less educated adopters than the segments of adopters who choose to purchase systems (Drury et al., 2012). Concerns about operation and maintenance have also been shown to be important predictors of solar PV leasing, as offerings may include such activities (Rai et al., 2016). Solar PV systems under third-party ownership also tend to be more performant than those under direct ownership (Guajardo, 2018). While leasing has been successful at facilitating the large-scale diffusion of solar PV in certain countries (EPA, 2022), its application to low-carbon heating is limited. Only a few studies dealt with heating-equipment leasing (Sovacool et al., 2021). Schleich et al. (2021) showed that rental models could contribute to the deployment of heating equipment in the United Kingdom. However, little is known about how households' preferences for heat-pump leasing vary in different countries.

3.2. Clean energy investment decision-making under uncertainty

Risk and return are determining factors in investment decisions in finance theory. Investment risk can be understood as the probability of occurrence and impact of specific factors on an investment outcome (Aven, 2016). The total level of risk of a clean energy investment is inherent of its features, e.g., the type of technology – see Hampl and Wüstenhagen (2012) for risk factors. In the realm of classical economics, expected utility theory serves as the dominant model for understanding investment decision-making under uncertainty (Karni, 2014). Investors are portrayed as rational agents with perfect information, whose self-interested decisions are guided by well-defined preferences (Persky, 1995). Investors consistently choose between investment options by weighting their expected pay-offs with the probability of obtaining these outcomes. Investors rationally choose the investment with the highest risk-adjusted return to maximize their expected utility (von Neumann and Morgenstern, 1944).

Criticisms of the underlying assumptions of classical theories led to a new understanding of effective investment decision-making (Aumann, 1997). Behavioural finance builds on theories of bounded rationality, whereby investors are viewed as agents with limited cognition and information (Simon, 1955). Given their finite capacity to process information and solve complex problems, boundedly rational investors rely on heuristics to make satisfactory – as opposed to optimal – decisions (Lucey and Dowling, 2005; Simon, 1956). This approach recognizes the influence cognitive factors and biases have on perceptions (Norton et al., 2012; Tversky and Kahneman, 1974, 1973). For example, investors may prefer familiar investment opportunities or may anchor their decisions in prior information rather than adjusting to new evidence – familiarity and anchoring biases, respectively (Baker and Ricciardi, 2014). Investment decisions are thus not strictly the result of objective inquiries but are also shaped by subjective preferences (Masini and Menichetti, 2013). Contrasting motivations, resources, and experience may thus result in different risk perceptions and return expectations for project developers, utilities, institutional investors, and homeowners.

Project developers ensure the development, construction, and early operation of projects using their own balance sheets (Hamilton and Zindler, 2016). As such, they take on higher levels of risk, especially in the case of less mature technologies (McInerney and Bunn, 2019). Higher levels of perceived risk translate into higher return expectations (Melliger and Lilliestam, 2021). Scholars have shown that developers use non-compensatory rules when choosing between investment options and value risk-

mitigating policies (Lüthi and Prässler, 2011; Lüthi and Wüstenhagen, 2012). Once projects are operational, developers sell assets for profits. Hence, they aim at minimizing production costs to maximize returns (Dinica, 2011).

Utility companies have historically been commodity suppliers, although their business model is expanding to the provision of energy services and power system solutions (Frei et al., 2018). These companies tend to be risk adverse, and finance assets using their own balance sheets (Hamilton and Zindler, 2016; Richter, 2013). While utilities invest at various phases of project development, they may require considerable premiums to take on early-stage activities (Salm, 2018). Utilities can also be slow at adopting innovations (Berlo et al., 2016; Helms et al., 2020). This may be explained by cognitive influences like status quo or confirmation bias, which bolster path dependency (Ertan et al., 2019; Unruh, 2000). Some firms have also been the driving force behind renewable energy diffusion when corporate strategy is aligned with policy changes (Stenzel and Frenzel, 2008). While several studies have investigated utilities' preferences for renewable energy investment, empirical evidence about preferences for energy storage investment is scarce.

Institutional investors – e.g., pension funds or insurance companies – have long-term, predictable liabilities, which prompt them to seek long-term, stable investment opportunities in several sectors (Gatzert and Vogl, 2016; Hamilton and Zindler, 2016). Their return requirements and risk propensity range between low to moderate, making them well-suited for investing in clean energy (IRENA, 2020a). Scholars have shown that institutional investors prefer outsourcing early project-development stages, and would require hefty premiums to take on such activities (Salm and Wüstenhagen, 2018). While policies that provide long-term visibility on cashflows have been conductive to institutional investment, perceptions of policy discontinuities are a major impediment (Polzin et al., 2015; Polzin and Sanders, 2020). Institutional investors could play an important role in financing grid modernisation (Polzin and Sanders, 2020). However, empirical evidence about their preferences for energy storage investment is scarce.

Households' decision-making related to heating systems has been extensively researched, with studies diverging in terms of technological focus, geographical scope, and household-specific aspects (Achtnicht, 2011; Karytsas, 2018; Laureti and Benedetti, 2021; Leurent et al., 2018; Michelsen and Madlener, 2016; Ruokamo, 2016). Scholars have shown that financial and technical factors such as investment cost and operational performance are important factors in heating decisions (Mahapatra and Gustavsson, 2008). Since the adoption of energy-efficient equipment like heat pumps can result in

energy cost savings (Rosenow et al., 2022), households may be regarded as investors who commit capital to benefit from financial returns (Bozorgi, 2015). As such, homeowners are willing to invest in new heating systems if this is perceived as being profitable with regard to cost savings and payback period (Achtnicht and Madlener, 2014). Beyond the cost-benefit calculus, households' decisions are also influenced by cognitive biases – e.g., whether loss averse or risk averse (Frederiks et al., 2015). Further, scholars have underlined the role heating services could play in mitigating risk for homeowners (Britton et al., 2021; Schleich et al., 2021). However, empirical evidence concerning their preferences for such services is scarce.

3.3. The effect of energy policies on investment decision-making

Energy policy plays a paramount role in shaping business models. Policy incentives can mitigate investment risk, increase return, and/or influence investors' risk-return perceptions (Wüstenhagen and Menichetti, 2012). De-risking investment is particularly relevant for clean energy technologies given their high upfront capital needs and sensitivity to financing costs (Schmidt, 2014). A variety of instruments exist, and have been subject to numerous scholarly inquiries – see Polzin et al. (2019) for a review. For example, feed-in-tariffs have historically played a key role in enabling the deployment of renewable energy capacity (Jenner et al., 2013). Growing concerns about over-subsidization have prompted a shift towards market-based incentives and auction schemes, which have become dominant support-allocation mechanisms (Gründinger, 2017). However, while auction schemes may foster cost-efficiency, they also introduce new risks for investors (CEER, 2020). Despite renewable energy sources becoming cost competitive with conventional technologies, scholars have warned against exposing projects to market risk too promptly, as this could hinder investment. Instead, they argue for the gradual phase-in of risk, conditional to the formation of a resilient investment ecosystem (Egli, 2020).

Beside the debate about the efficiency or effectiveness of different instruments in inducing investment, scholars have also highlighted the importance of policy scheme design (Haas et al., 2011). Notably, Botta (2019) showed that variations in auction scheme design can considerably affect bidders' return expectations. To promote citizen engagement and enhance project acceptance, policy makers in several countries have introduced auction design features to incentivize citizen participation (see *Paper 1* for

details). However, empirical evidence about the effect such measures have on developers is scarce.

Beyond renewable energy, scholars have also underlined the need for policy support to promote energy storage investment (Bell and Gill, 2018; Vorushylo et al., 2016). Particularly, they have highlighted the relevance of financial incentives in relation to making business models compelling to investors – e.g., grants, rebates, and tax credits (Faunce et al., 2018; Glenk and Reichelstein, 2019; Hossain et al., 2020; Moore and Shabani, 2016; Zame et al., 2018). Only a few studies have investigated the risk-return preferences of investors for energy storage investment (Krömer, 2019; Krömer and Gatzert, 2018). Scholars have shown that price risk is an important concern for investors and that preferences for investment in technologies such as pumped hydro may vary, highlighting the desirability of differentiated policies (Salm and Wüstenhagen, 2018). Besides policy support, power purchase agreements (PPAs) have also been highlighted as a means of mitigating risk for investors (Prapanukool and Chaitusaney, 2020). However, little is known about the influence policy incentives or other financial instruments have on investors' decisions for battery or hydrogen storage investment.

3.4. Conceptual framework

This section showed that the decentralization and servitization of business activities in the energy sector has led to the emergence of new financial mechanisms and business models. It also highlighted that, beyond risk and return, cognitive factors influence investors' risk perceptions and return expectations, and that these influences vary across investor groups. Further, it underscored the role energy policies have in rendering investments compelling for investors. The conceptual framework presented in Figure 1 illustrates how these elements relate to each other. It builds on the work of Wüstenhagen and Menichetti (2012), Hampl and Wüstenhagen (2012), and Salm (2017). This framework is used in this dissertation to clarify how different factors influence clean energy investment decisions and indicates how the research papers are related.

In *Paper 1*, we investigate how auction design elements aimed at fostering citizen participation influence project developers' risk perceptions and bidding decisions. Specifically, we focus on requirements pertaining to *financial pre-qualification*, *realisation period*, and co-investment (i.e., a *mandatory share offer to local residents*). These attributes were selected and designed based on the results of a pre-study, which comprised a review of literature on the factors affecting auction-participation decisions,

interviews with project developers, expert consultations, and prior research. Beyond being key considerations in investment decisions, the latter elements have also been used by policy makers to promote actor diversity in auctions.

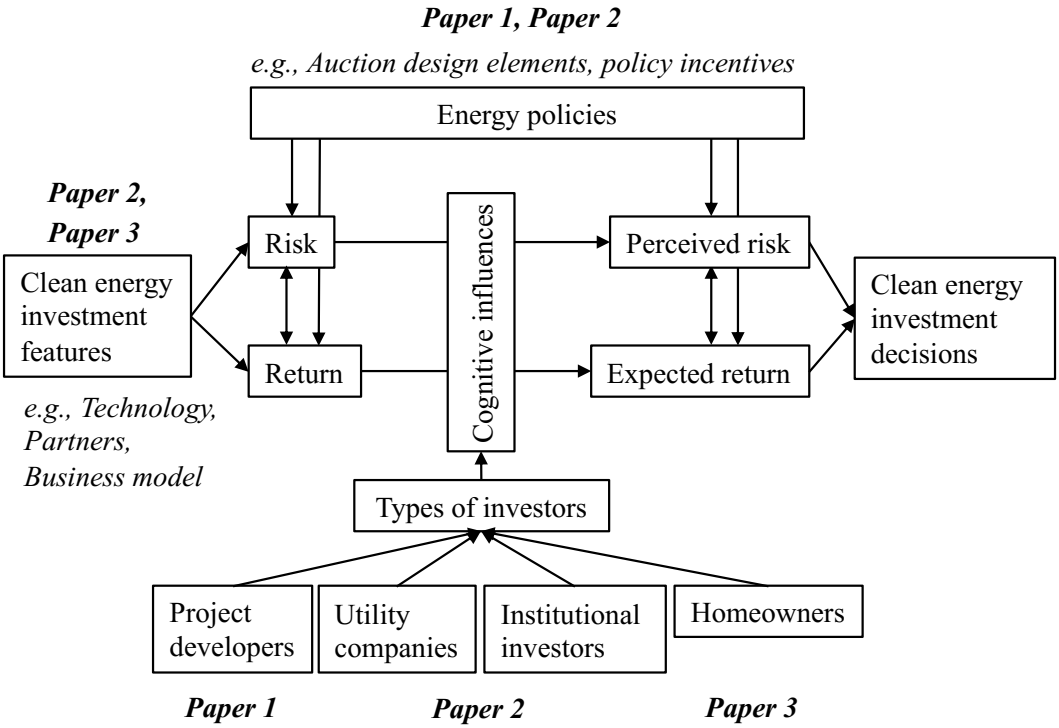


Figure 1: Conceptual framework applied in the dissertation. Source: author's construction, adapted from Wüstenhagen and Menichetti (2012), Hampl and Wüstenhagen (2012), and Salm (2017).

In *Paper 2*, we examine how factors relating to energy storage influence the investment decisions of utility companies and institutional investors. We focus on the type of *technology*, level of *fixed compensation* provided by various *partners* (e.g., German state via policy incentives or bilateral agreements with a company), and the type of *business model*. These attributes constitute important investment considerations and were designed based on the insights from a pre-study, similarly to *Paper 1*.

In *Paper 3*, I investigate how different *types of leasing contracts* and *service providers* influence homeowners' heat-pump leasing decisions. These attributes were chosen as they are important considerations in heating system procurement decisions. The focus is on a lease-to-own model, whereby homeowners have the option of purchasing the heat pump throughout the duration of the lease agreement, at the end of which they become its owner. The former can thus be regarded as investors who commit

capital to benefit from energy cost savings and to whom the ownership of the heat pump is eventually transferred.

4. Methodology

A sequential exploratory mixed-method design was used to clarify investors' preferences for clean energy investment and quantify their WTA risk and WTP for services. This strategy comprised two phases: 1) qualitative data were collected and analysed to explore the research topics; 2) building on these results, quantitative data were gathered and scrutinized to expand the understanding of the topics by using insights from larger groups of investors (Creswell, 2009). This approach is suited for this dissertation, as it enabled me to develop new research instruments and to obtain a detailed understanding of emerging research topics (Passey, 2020). A similar research design has also been used by scholars to investigate investors' preferences for renewable energy investment (Hille et al., 2018; Melliger and Lilliestam, 2021; Salm, 2018).

4.1. Qualitative phase

In the qualitative phase, semi-structured interviews with project developers (*Paper 1*), utility company representatives, and institutional investors (*Paper 2*) were conducted as part of pre-studies. The interviews included, among other elements, questions about investors' investment experience, factors driving their investment decisions, and perceived investment risks or barriers. The findings enabled me to gain a better understanding of investors' beliefs and attitudes regarding specific investment opportunities, and to identify the most important factors governing their investment decisions (Bryman, 2012). Additionally, a transdisciplinary approach was applied to validate pre-study findings using inputs from practitioners (*Paper 3*) (Rigolot, 2020). The insights collected in this first phase – along with findings from literature reviews, expert consultations, and prior research – contributed to informing the subsequent quantitative phase – namely, the design of choice experiments and survey instruments.

4.2. Quantitative phase

In the quantitative phase, three choice experiments were conducted with project developers (*Paper 1*), utility company representatives, institutional investors (*Paper 2*),

and homeowners (*Paper 3*) to elucidate their preferences for clean energy investment. This stated-preference method has its theoretical underpinnings in discrete choice and random utility theory (Manski, 1977; McFadden, 1974). It builds on the idea that investors derive utility from the attributes of investments, rather than from investments *per se* (Lancaster, 1966; Rosen, 1974). It posits that the total utility of an investment corresponds to the sum of its part-worth utilities – i.e., the utility associated with each attribute level of a hypothetical investment. Preferences are investigated by requiring experiment participants to systematically choose between different investment options that vary in terms of attributes levels. Participants are assumed to aim at maximizing their perceived utility given sets of financial constraints and choice alternatives. Although this approach relies on elements of classical theory, it enables researchers to examine the effect perceptions have on decisions, as these factors are likely to influence investors' estimation of the relative value of attributes (McFadden, 1980).

Choice experiments involve advantages and drawbacks. Since attribute levels are experimentally manipulated, the investment options that are presented to respondents can go beyond those observed on markets (Holmes et al., 2017). This makes this strategy particularly appropriate for investigation in this dissertation, as the objects under examination – i.e., citizen co-investment in auction settings, investment in battery and green hydrogen storage, and heat-pump leases – are typically at an early stage of diffusion (Louviere et al., 2000). The historical data about investment decisions that would be required to apply revealed-preference methods are limited or non-existent. Choice experiments also enable the estimation of specific effect on investment decisions, thereby providing relevant insights for policymaking (Alberini, 2019). However, this strategy has been criticized for being susceptible to strategic behaviour and hypothetical bias – i.e., deviating from market evidence (Hensher, 2010). Nevertheless, it has been broadly used to investigate investors' preferences for energy investment (Gamel et al., 2017; Petrovich et al., 2019; Vuichard et al., 2019). Notably, conjoint analyses[8] have been applied in the context of auctions (Botta, 2019), energy storage (Salm and Wüstenhagen, 2018), and heating services (Schleich et al., 2021).

Two conjoint methods were used in this dissertation: choice-based conjoint analysis (CBC), and adaptive choice-based conjoint analysis (ACBC). CBC is a realistic approach to examining decision-making that requires investors to systematically state

[8] Conjoint analyses are understood as decompositional methods used to estimate the structure of agents' preferences based on the attribute levels of alternatives (Rao, 2014).

their preferred options among sets of hypothetical investments that vary randomly in terms of attributes levels. Choice tasks are simple, easy to understand, and closely mimic the real choice settings of investors (Johnson and Orme, 2007). As such, CBC is the most widely used conjoint method (Rao, 2014). It was applied in *Paper 1* and *Paper 3*. ACBC may involve both screening and choice tasks. Screening tasks include self-explicated questions, thereby enabling investors to indicate unacceptable levels to clarify cutoff rules. An ACBC was applied in *Paper 2*, as clarifying heuretics was of interest.

Hierarchical Bayes (HB) models were specified to estimate part-worth utilities – i.e., the relative preferences of investors for specific investment features (see papers for details). Following Salm and Wüstenhagen (2018), aggregated WTA values were estimated using part-worth utility results (see *Paper 1* and *Paper 2*). This allowed us to quantify the compensation that investors would require to be willing to accept an investment with less preferred features compared to one with the most preferred features. Following Kaenzig et al. (2013), aggregated WTP values were estimated (see *Paper 3*). This allowed me to ascribe a monetary value to the amount homeowners would be willing to pay for an offering with preferred features compared to one with the least preferred features.

5. Conclusion

This dissertation clarifies the preferences of investors for clean energy investment and quantifies their WTA risk and WTP for services. Obtaining a better understanding of how the attributes of energy policies and business models influence investors' risk perceptions and return expectations enabled me to uncover financial mechanisms, business models, and incentives that may promote investment. In this section, I first outline the empirical contributions of this dissertation by summarizing the main findings of the three research papers. Second, I discuss practical implications for policy makers and investors. Third, I specify the limitations and suggest future lines of research.

5.1. Empirical contributions

This dissertation makes important empirical contributions, notably to research on social acceptance, renewable energy auctions (*Paper 1*), energy storage (*Paper 2*), service-based business models (*Paper 3*), and investor decision-making (all papers).

In *Paper 1*, we deepen the understanding of how auction design elements aimed at fostering citizen participation influence project developers' risk-return requirements. This study is the first empirical contribution to research on renewable energy auctions that examines citizen co-ownership schemes through the lens of developers. We show that developers are sensitive to several risks embedded in auctions. While policy makers have introduced lower bid bonds to promote citizen participation, our results suggest that developers are willing to accept *financial pre-qualifications* of up to a certain level. Overall, developers require only a small premium to move from an auction with a 5,000 €/MW bid bond to one with 30,000 €/MW. However, they would demand an average premium of 1.79 percentage points to accept a 70,000 €/MW bid bond, the largest risk premium that was identified when considering all respondents. These findings indicate some aversion towards allocation risk, supporting research that shows that this risk is regarded as the most important one in auction settings (Đukan and Kitzing, 2021).

As for the *realisation period*, while longer time horizons have been introduced to foster citizen participation, our results suggest that developers generally prefer a moderate period of 36 months. Small and medium-sized developers require an average 0.97 percentage point premium to move from an auction with a 36-month period to one with 54 months. In contrast, larger developers do not differentiate much between a moderate and long period, but would require a 2.37 percentage point premium to move from an auction with a longer realisation period to one with 24 months. These results may reflect the fact that smaller firms are more agile than larger ones, providing them with a relative advantage when moving quickly is required (Hockerts and Wüstenhagen, 2010). Regarding a *mandatory share offer to local residents*, while developers appear to be generally open to co-ownership, they would demand 1.3 percentage points in compensation to bid in an auction at which 20% of project equity is required to be open to citizen co-investment compared to a setting where no co-investment is required. Larger developers would require a premium nearly twice as large as smaller firms. These results support studies suggesting that smaller developers have a superior ability to interact with local stakeholders (Goedkoop and Devine-Wright, 2016).

In *Paper 2*, we provide empirical insights into the risk-adjusted preferences of utility companies and institutional investors for battery storage and green hydrogen investment. Similarly to prior research (Salm and Wüstenhagen, 2018), our results show that exposure to electricity price risk is an important factor in investment decisions. Institutional investors would require an average risk premium of 6.87 percentage points to move from an investment in which 100% of revenue is fixed to one with only 20%

fixed compensation, whereas utilities would demand 5.54 percentage points. Securing fixed returns appears to be even more critical for institutional investors than utilities, as this attribute was found to be the second most important factor in their investment decisions, after the expected return. Utility respondents would prefer to obtain fixed compensation from the German state. While institutional investors do not differentiate much between who provides the fixed compensation (the state or a corporation), they see a lack of governmental support as one of the most important barriers to investment, along with a lack of available business cases. As such, they prioritize applications which are likely to generate stable returns like primary control services.

Further, we show that institutional investors prefer outsourcing project development, construction, and operation, and would require an average premium of 3.75 percentage points to take on these activities, although 23% of respondents revealed that this would be unacceptable for their company. In contrast, utilities prefer to take on such activities, and would demand a compensation of 2.45 percentage points to outsource them. These findings deviate from those of prior studies which show that both investor groups prefer owning renewable energy assets and outsourcing other activities (Salm, 2018). It may explain why utilities seem to be more reluctant than institutional investors to invest in new technologies, as their technical know-how may be limited. Indeed, our results show that both investor groups have comparable risk-return preferences for investment in more mature *technologies* like battery storage combined with solar PV. However, utilities would require an average premium about twice as large as that of institutional investors to invest in projects involving the integration of solar PV with green hydrogen production and storage. These findings support studies which find that utilities tend to be slow at adopting innovations (Berlo et al., 2016; Helms et al., 2020).

In *Paper 3*, empirical insights into homeowners' preferences for heat-pump leasing represent one of the first contributions to research on service-based business models for low-carbon heating with a focus on the perspective of end-users (Schleich et al., 2021). Survey results show that asset leasing could address some of the challenges homeowners face with regard to heat-pump adoption in France, Germany, and Switzerland. Leasing decisions are predominantly driven by the level of *monthly lease payments* and the *type of lease contract.* Homeowners prefer offerings associated with lower payments, in which the heat pump, its installation, yearly maintenance, and potential repairs are all included. Their average WTP for an all-inclusive package compared to a basic one that would only include the heat pump and installation is similar across the three countries. However, German homeowners would be willing to pay nearly three times as much as

their French counterparts for an all-inclusive package as opposed to a maintenance package, in which only the heat pump, installation, and yearly maintenance are included. Swiss homeowners would also be willing to pay more for subscription-based repair services. These findings suggest that German and Swiss homeowners differentiate more than the French between all-inclusive and maintenance packages. They also point to an apparent reluctance to take on any technical risk. While homeowners prefer services from a heating specialist or local energy utility, diversifying the types of *service providers* may be desirable for meeting the needs of different end-users.

Additionally, the results indicate that preferences for leasing or purchasing vary across countries. German homeowners are those most likely to leasing a heat pump, as 44.7% of respondents planning to install such device expressed a strong preference for leasing as opposed to 24.5% who strictly prefer purchasing. In contrast, Swiss homeowners are the least likely to lease, as only 19.8% of respondents revealed a strong preference for leasing and 55.9% for purchasing. This may be explained by the greater affluence of Swiss homeowners, and the low level of heat-pump diffusion in Germany. While these insights highlight the relevance of asset leasing, especially for markets where heat pumps are at an early stage of diffusion, the results also underline the importance of offering flexible contracts since the length of leases appears to be a major drawback for homeowners. These findings support research showing that service-based offerings could contribute to decarbonizing residential heat (Sovacool et al., 2021).

5.2. Practical contributions

The empirical insights presented in the previous subsection contribute to a better understanding of the dynamics of the policy-investment nexus. They enable me to define evidence-based policy implications and business models that may promote clean energy investment. As such, they also contribute to energy policy research. In this subsection, I summarize key practical contributions for policy makers and investors.

In *Paper 1*, the empirical insights allowed us to define three policy implications that could help policy makers to find the right balance between cost-reducing and risk-increasing auction design. First, since moderate *financial pre-qualifications* do not seem to considerably influence developers' risk-return requirements, policy makers may wish to consider their use to ensure the timely realisation of projects. Second, as developers appear to prefer moderate project *realisation periods*, well-meaning policy makers who

believe longer time horizons promote actor diversity may want to bear this preference in mind, as very long periods could be perceived by some investors as increasing risk rather than lowering it. Further, shorter realisation periods are associated with some of the largest risk premiums, particularly for larger developers, perhaps reflecting the permitting-related issues observed in several markets. Policy makers could consider adapting permitting regimes by building institutional capacity and creating one-stop shops, which could contribute to shortening realisation periods and reducing risk for investors. Third, our results show that promoting actor diversity in the context of auction comes at a price. Since there is an apparent trade-off between incentivising citizen co-investment and creating low-cost projects, policy makers who are unwilling to compensate developers for the risk and complexity associated with citizen co-ownership will have to find other ways to foster actor diversity and social acceptance. Otherwise, this may hinder renewable energy investment and jeopardize the achievement of climate goals. As such, more exemptions from auctions for community-based and/or citizen-driven projects could be considered.

In *Paper 2*, the empirical insights underline the relevance of policy support for promoting energy storage investment. We show that mitigating electricity price risk for institutional investors and utility companies through the provision of *fixed compensation* may considerably lower financing costs. Since both investor groups prefer to obtain support from the German state, policy makers interested in promoting energy storage capacity could consider expanding policy schemes such as fixed-price premiums to support assets. While regulated revenue from frequency control reserve and innovative auctions have contributed to the deployment of battery storage in Germany, current auction volumes are unlikely to foster the level of investment needed to match the country's decarbonization ambitions (Battista, 2021). Scaling up auction volumes could provide a way to mitigate price risk, especially in relation to battery storage, since both investor groups view this technology as more mature than green hydrogen production and storage. Beyond policy incentives, our results also highlight the role corporate PPAs could play in providing stable returns, especially for institutional investors who do not seem to differentiate much between fixed compensation provided via a state incentive or bilateral agreements with international companies. Further, given that the two investor groups have complementary preferences when it comes to taking on development, construction, and operation risk, policy makers could consider facilitating the creation of joint ventures by incentivizing utility companies to engage in greenfield activities and support institutional investment at later stages. Finally, as investors would require considerable premiums to invest in green hydrogen *technologies* compared to

battery storage, policy makers may wish to focus on supporting such projects when the application of battery storage is limited to ensure the efficient allocation of public resources.

In *Paper 3*, empirical insights into homeowners' preferences for heat-pump leasing allowed me to define three main implications for policy makers and service providers. First, given that service-based offerings like asset leasing could contribute to facilitating the diffusion of low-carbon heating solutions, policy makers who wish to promote the adoption of heat pumps could consider providing support tailored to different modes of adoption – i.e., outright purchase, or the procurement of heating services. For example, fiscal regimes could be reformed so that monthly leasing fees become tax deductible for homeowners, as proposed by Schleich et al. (2021). Second, a variety of industry actors such as heating specialists, utility companies, and manufacturers could consider providing all-inclusive heat-pump lease offerings, in which the heat pump, installation, yearly maintenance, and potential repairs and part replacement costs are included. Performance guarantee could also be offered if operational performance is a concern, such as for German homeowners. Third, *service providers* may wish to consider including an option to terminate the lease contract at any time by paying the reminder of what is owed for the heat pump and installation (lease-to-own), as the length of contracts is a drawback for homeowners.

5.3. Limitations and avenues for future research

This dissertation addresses important issues pertaining to clean energy investment. While it provides valuable insight into how specific factors related to clean energy investment shape investors' decisions, the solutions proposed in this section by no means exhaustively address all the investment challenges posed by the energy transition. Considerable research effort is still necessary in view of the need to mobilize the volume of clean energy investment required to achieve net zero. In this subsection, I discuss the overarching limitations of the papers and propose future lines of research. Study-specific limitations can be found in the subsequent chapters of this dissertation.

First, stated-preference methods were used to elucidate investors' risk-return requirements. This approach is appropriate in this context as the historical data on investment decisions that would be required to apply revealed-preference methods are limited. However, investors may not act immediately upon their stated preferences,

which could leave a gap between intentional and actual investment decisions. Since data was obtained by relying on hypothetical choice settings rather than real-life situations, investment decisions may also be biased by the hypothetical nature of the experiments. This could result in overestimated WTA and WTP values (Kanya et al., 2019). It is perhaps worth clarifying that the aim of this dissertation was not to derive precise measurements of WTA and WTP, but rather to test the importance of specific attributes and levels in investment decisions. Hence, the WTA and WTP estimates illustrate the relative ranking of levels and may be regarded as indications of the limits of what investors are willing to accept or pay (Kaenzig et al., 2013). Several calibration techniques like cheap-talk scripts and budget reminders were used in all papers to alleviate hypothetical bias (Hensher, 2010). The choice experiments also proposed discrete choice tasks instead of asking directly for attribute-specific preferences to curb potential biases. Once sufficient data is available, further research could elaborate on actual investment decisions using revealed-preference methods.

Second, this dissertation uses a sequential exploratory mixed-method design, whereby the results of qualitative analyses serve as input for the subsequent quantitative analyses. This design is different from a sequential explanatory strategy where the qualitative phase is conducted after the quantitative one (Creswell, 2009). Pursuing a sequential exploratory strategy was useful in this context as it enabled me to obtain a detailed understanding of emerging research topics whilst contributing to the development of new instruments (Passey, 2020). However, this design may have limitations with regard to explaining some of the quantitative results. Further research could build on the findings of this dissertation using qualitative methods like focus groups to further explore investors' attitudes and perceptions – e.g., could elaborate on project developers' risk perceptions with regard to citizen co-ownership (*Paper 1*).

Third, the representativeness of the respective data sets limits the external validity of the findings. This dissertation focused on European onshore wind energy project developers (*Paper 1*), institutional investors, and representatives of utility companies active in Europe (*Paper 2*), and French, German, and Swiss single-family house owners (*Paper 3*). However, the issues addressed in this research endeavour go beyond these geographical areas or technological foci. Further research could explore how investment preferences vary in other markets – e.g., the preferences of developers for citizen co-ownership schemes could be investigated in the context of solar energy auctions, as this technology is also foreseen to play an important role in decarbonization efforts and is subject to opposition.

This dissertation has underlined the importance of expanding our understanding of investor behaviour in view of the need to mobilize the clean energy investment required to achieve net zero. It has also highlighted the critical role energy policy and investor cognition play in shaping investment decisions. While it has generated valuable insight that may serve as basis for informing efficient policymaking, this dissertation has also shed light on new business opportunities for investors. Moving from insights to impact will require additional research and the practical implementation of climate solutions. Although policy makers have a duty to implement measures to prompt clean energy investment, they also have the difficult task of balancing competing interests to avoid creating windfall profits for investors. Nevertheless, failing to address the investment challenges related to the energy transition could jeopardize life on Earth. It is thus the collective responsibility of policy makers, investors, and scholars to further work at tackling these important questions as, ultimately, clean energy investment is investment into the future.

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Paper I. The price of actor diversity: Measuring project developers' willingness to accept risks in renewable energy auctions[9]

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Abstract

Renewable energy (RE) auctions were partly introduced to lower the cost of policy support. However, policymakers are increasingly aware that effective policies require a broader set of objectives that include securing actor diversity and social acceptance. While several countries have introduced measures to incentivize citizen participation in RE projects to meet those objectives, little is known about their effect on the risk perceptions of developers in auction settings. Based on insights from 559 experimental choices made by 61 European project developers, this study investigates risk-return preferences for different onshore wind energy auction designs. We show that developers are willing to accept the requirement to submit bid bonds up to a certain threshold, and that a 36-month realisation period is preferred overall. While developers may be open to citizen co-investment, the risk premiums they require increase with the share of capital offered to local residents in auction settings, highlighting an apparent trade-off between promoting actor diversity and low-cost RE deployment. Policymakers unwilling to compensate developers for the price of increasing actor diversity may have to find other ways to promote citizen participation in order to achieve RE objectives, as this factor may have important implications for the acceptance of RE deployment.

Keywords: Renewable energy auctions, Citizen participation, Risk premium, Investment decision, Choice experiment, Social acceptance.

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1. Introduction

To foster the deployment of renewable energy (RE) at the lowest possible cost to taxpayers and energy consumers, the European Commission proposed in 2014 a shift from administratively-set support schemes to competitive tendering (EC, 2019, 2014). Since then, auctions have become the dominant instrument for allocating financial support to RE projects across the European Union (EU) (CEER, 2020). Auctions introduce new risks for project developers and have been shown to create disproportional challenges for smaller actors such as RE communities (Grashof, 2019; Morris, 2019; Tews, 2018). Further, RE projects – in particular, onshore wind – are also facing growing opposition in many countries, which often results in additional risks and delays for developers (Brindley and Fraile, 2021; IEA, 2020; Quentin, 2019). In this context, the European Commission called for a more proactive role of citizens in decarbonization efforts to foster the acceptance and deployment of RE infrastructure (EC, 2015). This has become even more relevant in light of recent renewed ambition to engage in climate action.[13]

Research shows that citizen participation plays an important role in fostering the acceptance of RE projects (Bauwens and Devine-Wright, 2018; De Luca et al., 2020; Hvelplund et al., 2017; Vuichard et al., 2019), including financial participation through citizen investment (Johansen and Emborg, 2018; Lienhoop, 2018; Musall and Kuik, 2011; Warren and McFadyen, 2010). However, projects with shared ownership – i.e., RE assets jointly owned by professional developers and local citizens through, for example, co-investment schemes – may be associated with increased risk and costs for developers (Goedkoop and Devine-Wright, 2016). In an effort to increase citizen engagement and local acceptance, EU legislation mandates that Member States introduce provisions aimed at enabling citizen participation in RE projects through a variety of measures, including community-based co-investment and joint ownership models (European Parliament and Council of Europe, 2019, 2018). The European Commission also plans to periodically assess the performance of national RE auction schemes to ensure their suitability according to several criteria – namely, cost-

[13] In April 2021, the European Parliament and Council of Europe reached partial agreement on increasing the stringency of the 2030 target for greenhouse gases emission reductions from a 40% to a 55% reduction (European Parliament, 2021). This has led to an upward revision of the EU's current 32% RES target to at least a 40% RES share in final energy use by 2030, which itself would require a threefold increase in the 179 GW of wind power capacity installed today (EC, 2021, 2020; WindEurope, 2021). The European Commission expects Member States to use RE auctions to operationalise more predictable RE power capacity deployments, both in terms of support cost (competitiveness) and pace (timeliness) (EC, 2020; European Parliament and Council of Europe, 2018).

effectiveness, actor diversity, and local acceptance of RE infrastructure (European Parliament and Council of Europe, 2018).

Auction designs vary across countries (del Río and Kiefer, 2021), and can be tailored to meet different policy objectives (Mora et al., 2017a). Until now, only a few EU Member States have introduced specific auction design elements to incentivize citizen participation (BMWi, 2017; CRE, 2020; DECC, 2020a). Their experience exemplifies how tailoring auctions to ensure actor diversity remains a challenging endeavour (Mora et al., 2017a). Indeed, these measures have typically resulted in a low share of successful bids that included citizen participation (Gsänger and Karl, 2020; Rüdinger, 2019), suggesting a limited understanding of bidders' risk perceptions. To fill this gap, our study addresses the following research question:

How do different auction design elements aimed at fostering citizen participation influence the risk perceptions of RE project developers, and their willingness to participate in auctions?

Our study addresses this question by drawing on insights from a choice experiment conducted with 61 European onshore wind energy project developers who made a total of 559 experimental decisions. The objective was to investigate the risk perceptions of developers with regard to various actor-specific auction design elements and shed light on their preferences for different forms of citizen participation. In doing so, this study contributes to research on RE auctions, citizen participation, and investor decision-making. In particular, it contributes to the growing academic and policy debate about how actor diversity can be fostered in the context of RE auctions (Álvarez and del Río, 2022; Grashof, 2019), and to the discussion about policies aimed at mandating citizen co-investment (Goedkoop and Devine-Wright, 2016; Rüdinger, 2019). Gaining a better understanding of how auction design elements influence the risk perceptions of project developers allows us to derive evidence-based policy recommendations that may help policymakers to find the right balance between cost-reducing and risk-increasing auction designs.

The remainder of this study is structured as follows: Section 2 reviews key auction-related risks and existing actor-diversity measures introduced in RE auction settings. Section 3 elaborates on the methodological approach and experimental design. Section 4 reports and discusses the results of the choice experiment. Section 5 concludes by

summarizing key findings, discussing policy implications, and suggesting future lines of research.

2. Background and literature review

The introduction of RE auctions was triggered by a perception that previous support schemes may have been overly generous to some RE producers, while simultaneously becoming increasingly costly for electricity end-users (Gründinger, 2017; Vorholz, 2012). As the cost of RE support is ultimately borne by consumers, policymakers are concerned about the cost-effectiveness of support schemes, and would like to avoid situations where investors capture higher profits than needed to achieve energy targets. Previous research on RE policymaking has shown that perceived risk is an important moderator of policy effectiveness, and that attempts at reducing policy cost may come with increases in risk (Lüthi and Wüstenhagen, 2012). Since investors do not only look at returns, but at risk-adjusted returns, policies aimed at maximizing cost-effectiveness may unintentionally crowd out investors who perceive the return of a policy scheme as being too low to compensate for the risk. This could result in (a) a lack of actor diversity, meaning only those investors with the lowest return expectations and/or the greatest ability to absorb risk remain, or even (b), a failure to reach policy targets if the remaining investors are unable to mobilize sufficient capital (Karneyeva and Wüstenhagen, 2017). Both effects are counterproductive for effective long-term policies. In the case of actor diversity, there are concerns that a negative feedback loop could occur if small, local developers are crowded out, potentially accentuating social acceptance challenges. Therefore, policymakers would be well advised to not just monitor the short-term cost-effectiveness of policies, but to keep an eye on investors' risk perceptions and the required risk-adjusted returns of different investor types, including those who take on board citizen co-investment.

As with other RE policies, it is the specific design elements of auctions that determine the risk-return expectations of investors. To understand how auction design elements influence risk perceptions, this section first reviews salient auction-related risks and their impact on different types of bidders. It also provides examples of actor-specific measures introduced in some European auction schemes to mitigate these risks and promote actor diversity. In doing so, it lays the foundations for the following analysis and discussion.

2.1. Overview of risks to project developers in renewable energy auctions

Several auction design elements have the potential to influence risks and returns for investors (Polzin et al., 2019; Winkler et al., 2018). Auction-related risks vary at different project development stages, and their impact depends on bidders' size, financial robustness, and business model (Đukan et al., 2019). This section provides an overview of how allocation, planning, qualification, non-compliance, and shared ownership risks may affect larger and smaller bidders. These risks represent key considerations in the decisions of developers to participate in RE auctions, and have in most cases been targeted by policy measures aimed at promoting actor diversity in auction settings (see Subsection 2.2 and 3.3). They are thus operationalized in the subsequent choice experiment through the inclusion of different levels of competition, bid bonds, realisation periods, and citizen co-investment requirements. Beyond this, auction design elements that may also affect exposure to other risks are specified as constants in the choice experiment to avoid dominant effects, enabling a focus on specific actor-diversity measures. These include, for example, the type of remuneration schemes which influence exposure to price risk, and the choice of pricing rule which may induce strategic bidding and increase the risk of project non-realisation (Polzin et al., 2019).[14] Figure 1 summarizes the conceptual framework used in this study.

[14] The remuneration scheme determines the payment mechanism a public entity provides to financially support successful bids, while the pricing rule defines the mechanism of selecting winning bidders and awarding support to them (AURES II, 2019a, 2019b).

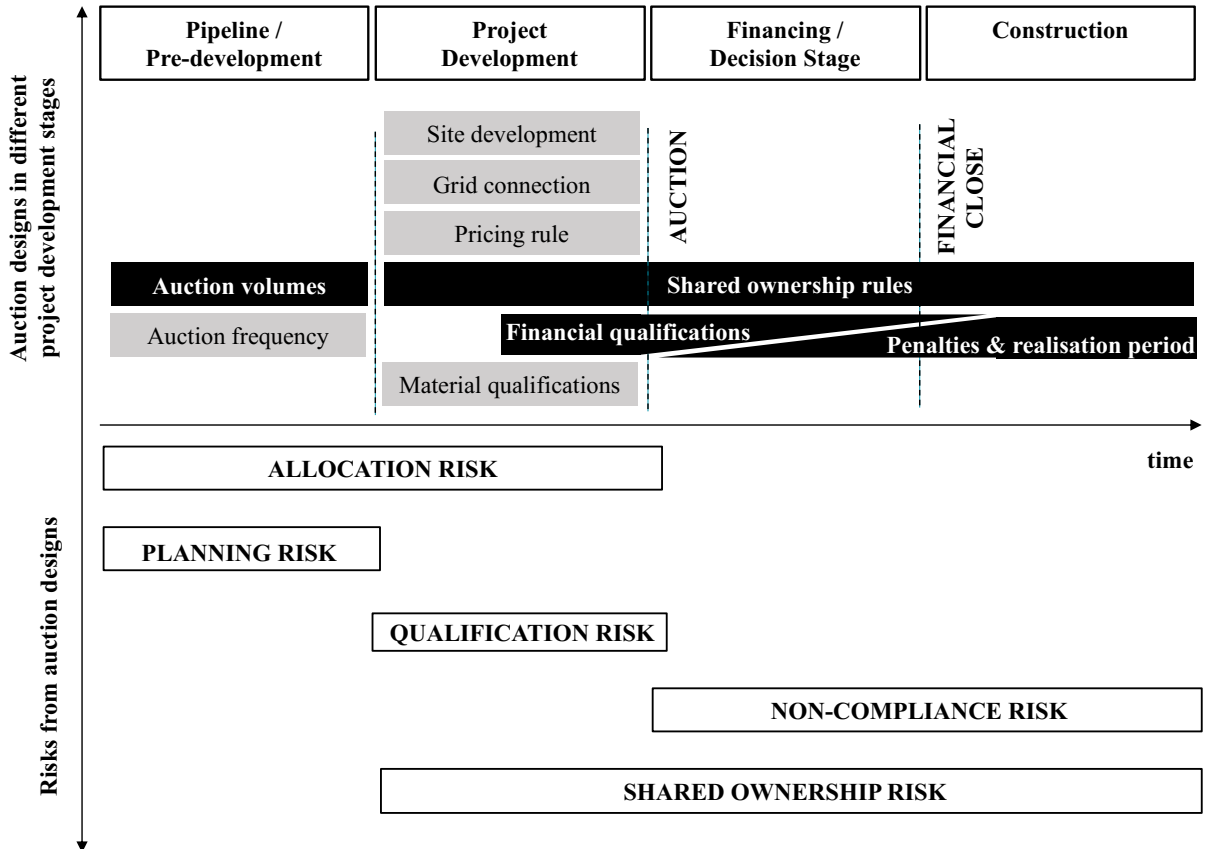


Figure 1: Schematic overview of major risks associated with different auction design elements, their appearance in the project development process, and their duration. The black boxes represent the auction design elements that are considered within the scope of this study, while the grey boxes represent the elements that are outside of its scope. The list of auction design elements is not exhaustive.

2.1.1. Allocation risk

The risk of (not) obtaining support – i.e., allocation risk – is the largest source of risk introduced by auction-based support schemes (Đukan and Kitzing, 2021). As such, auctions create structures whereby developers invest resources into projects while remaining uncertain of their financial viability until results are announced (Botta, 2019). Since larger bidders are usually more financially robust than smaller developers, they are less exposed to allocation risk. They tend to develop large project portfolios and benefit from several revenue streams, thus diversifying the risk of sunk costs that project failures may incur (Đukan et al., 2019).

In contrast, smaller developers who operate locally – particularly citizen-led organisations – may follow a "one-project approach" (Lucas et al., 2017). As such, their

relative exposure to sunk costs is greater. Further, they may face local constraints like limited space or wind resources, which may hinder resource-optimization. Smaller actors tend to have higher capital expenditure due to their limited capacity to benefit from economies of scale (Grashof, 2019). Additionally, citizen-led organisations are also not exclusively profit-driven but instead emphasize principles like procedural and distributional fairness, environmental stewardship, and community empowerment (Fischer et al., 2021; Holstenkamp and Kahla, 2016; Seyfang et al., 2013; Yildiz et al., 2015). These characteristics can result in relatively high costs, which may be offset by lower return requirements, or decrease price competitiveness and increase exposure to allocation risk. Beyond these actor-specific characteristics, allocation risk is also amplified by exposure to other types of risk; in particular, planning, qualification, non-compliance, and shared ownership risks.

2.1.2. Planning risk

Auctions are volume-based support allocation mechanisms (Held et al., 2014) in which an authority defines the volumes of a good to be auctioned and plans an auction schedule accordingly. Defining and communicating such RE support rollout provides clarity to investors about future market demand (Gephart et al., 2017). Organising long-term, continuous auction schedules increases certainty compared to short-term "stop-and-go" schedules (Mora et al., 2017b; Wigand et al., 2016), and reduces planning risk – a risk caused by auction volumes and frequency and their effects on project development uncertainty.

Planning risk is closely linked to allocation risk, mainly because auction volumes also affect the level of competition – i.e., the ratio between the expected volume of power capacity submitted by auction participants and the volume of power capacity tendered by the authority conducting the auction (the auctioneer). Setting auction volumes at levels at which the auctioned RE capacity is relatively scarce compared to the potential volume of the submitted projects may increase the level of competition and reduce support costs (del Río, 2017; del Río and Linares, 2014; Winkler et al., 2018). While this increases allocation risk, it also affects planning risk, as project developers have less clarity in their ability to recuperate development costs. This can particularly affect smaller actors who develop small-scale and less cost-efficient projects. In contrast, larger developers who operate internationally and who seek sites with greater

resources can tap into multiple markets. This increases their relative competitiveness and reduces their exposure to planning risk.

2.1.3. Qualification risk

When preparing for an auction, bidders often have to meet material and financial qualification requirements – e.g., by securing building permits or submitting financial guarantees (Soysal and Kurgpold, 2016). In the latter case, developers must submit bid bonds to qualify for auction participation, and/or performance bonds to ensure timely project realisation. Such requirements may decrease the short-term financial liquidity of bidders, especially when balance sheets are small relative to the size of guarantees required (Đukan et al., 2019). As such, they may constitute a barrier to auction participation for capital-constrained actors (Held et al., 2014; IRENA and CEM, 2015; Wigand et al., 2016) – in particular, for smaller developers or community-led organisations (Botta, 2019).

2.1.4. Non-compliance risk

Auctioneers implement penalties by retaining financial guarantees when bidders fail to comply with contractual agreements – e.g., if projects are not realized within a specific timeframe (Soysal and Kurgpold, 2016). Shorter realisation periods may increase non-compliance risk – i.e., the risk of incurring penalties in the case of non-compliance with the requirements defined in the awarded support contract (Hochberg and Poudineh, 2018; IRENA and CEM, 2015). Smaller and less experienced developers have less expertise dealing with pitfalls during the permitting process (Amazo et al., 2020). This makes them more vulnerable to breaching realisation deadlines than their larger counterparts if permits are procured after auctions. As described in Subsection 2.1.1, smaller actors also have less ability to spread the cost of paying penalties due to the limited size of their project portfolios. In contrast, longer realisation periods could reduce their exposure to non-compliance risk. However, it could also stimulate underbidding and speculative behaviours by allowing bidders to postpone their final investment decisions to when the actual costs and benefits of developing a project become clearer (del Río and Linares, 2014; Matthäus et al., 2021).

2.1.5. Shared ownership risk

Auctioneers can introduce different auction design elements to foster citizen co-investment (del Río, 2017; Lundberg, 2019). However, promoting (or even mandating) shared ownership can pose several challenges to developers. While co-investments might enable developers to mitigate the risk of public contestation – thereby increasing the likelihood of securing building permits (Goedkoop and Devine-Wright, 2016; Slee, 2015) –, trust plays a central role in the success of such arrangements (Kalkbrenner and Roosen, 2016). Locally embedded developers who share local values might have an advantage over external developers who would need to allocate substantial resources to locate, mobilize, and entrust local citizens (Goedkoop and Devine-Wright, 2016). Larger external developers may thus be more exposed to the risk of failed co-ownership than smaller actors. Local constraints such as population density, average income, and project concentration may also limit the amount of citizen capital available (FPF, 2017). This could challenge the realisation of shared ownership initiatives and increase bidders' exposure to financial and non-compliance risks. Other aspects of co-investment schemes like the method used to determine the price of shares or the minimum holding period can also influence exposure to shared ownership risk for developers.

2.2. Auction design elements to mitigate risks and promote actor diversity

To inform the design of our choice experiment, this subsection provides an overview of how some European countries have implemented auction design elements to address the risks presented in Subsection 2.1 and promote actor diversity. While several EU Member States have introduced specific actor diversity measures, the overview presented here provides details on the German, French, and Irish experiences. To the authors' knowledge, only these three countries had implemented design elements calibrated to induce greater actor diversity in their national auction schemes at the time of writing. These cases are also of particular interest as they illustrate contrasting approaches in terms of policy measures, timing, duration, and experiences yielded thus far for incentivising greater citizen participation. A brief overview of these design elements and their outcomes are reviewed and summarised in Table 1.

2.2.1. Financial qualification

To decrease qualification and allocation risks, auctioneers can calibrate financial guarantees to different actor types. For instance, both Germany and France introduced a 30,000 €/MW bid bond requirement in their onshore wind energy auctions (see Table 1). While France maintained the same requirement for all auction participants, Germany initially differentiated between actor groups by imposing a 15,000 €/MW bid bond on 'community energy companies' (CECs). However, the auctioneer withdrew this preferential rule in 2018, and instead applied a uniform bid bond of 30,000 €/MW for all bidders. Similarly, Ireland's first RE auction required a 2,000 €/MW bid bond and a 25,000 €/MW performance bond from all participants, except for some community-led projects.

2.2.2. Realisation period

To reduce non-compliance risk, auctioneers can also differentiate between different actor-specific realisation periods. For instance, France and Ireland imposed a 36-month and 23-month realisation period, respectively, for all auction participants (see Table 1). In contrast, Germany initially imposed a 30-month realisation period for commercial developers, and 54 months for CECs. However, the auctioneer rescinded this preferential condition in 2018 and imposed a 30-month realisation period for all auction participants.

2.2.3. Shared ownership

In 2017, Germany introduced preferential conditions for projects with citizen ownership, including less stringent material and financial pre-qualification requirements, a longer realisation period, and actor-specific pricing rules (BMWi, 2017). However, all preferential conditions were withdrawn in 2018, except for the pricing rule. In tandem with Federal provisions, the state of Mecklenburg-Vorpommern also introduced a law obliging project developers to offer local residents and municipalities the possibility to invest in projects and own at least 20% of shares in project companies, irrespective of their participation in auctions (GVOBl. M-V S. 258, 2016).

Table 1: Overview of onshore wind auction design elements for inducing citizen participation in the German, French, and Irish auction schemes, and their outcomes. Source: Authors' elaboration based on BGBI (2020), BMWi (2017), Bundesnetzagentur (2017a, 2017b, 2017c), CRE (2020, 2018a, 2018b, 2017), DECC (2021a, 2021b, 2020a, 2020b), Eirgrid (2020), Énergie Partagée (2020), Pié (2021).

	Germany	France	Ireland
Auction design elements			
Financial qualification	- 30,000 €/MW bid bond (2017 only: 15,000 €/MW for citizen energy companies (CECs))	- 30,000 €/MW bid bond	- 2,000 €/MW bid bond and 25,000 €/MW performance bond for all bidders, except some community-led projects (2020 round); 7 €/MWh bid bond and 24 €/MWh performance bond (2022 round)
Realisation period	- 30 months (2017 only: 54 months for CECs)	- 36 months	- 23 months
Citizen participation	- 2017: preferential rules for CECs (i.e., lower bid bond, no material pre-qualification, longer realisation period, and uniform pricing) - 2018: preferential rules suspended, except uniform pricing - 2021: new voluntary payments to local municipalities scheme, operating outside tenders	- 2017: bidders offering capital shares to local residents benefit from additional premiums - 2018: crowdfunding and participatory investment modalities are specified - Today, participatory premium under review, to substitute by points-based ranking system (95% of points for price, 5% for citizen participation)	- Preference category for 'Community-led Projects' (separate from developer-led projects) - 'Community' category projects exempt from financial and performance guarantees, and independent pricing assessment - Contribution to community benefit fund for all bidders, irrespective of category
Auction outcomes			
Level of competition and actor diversity	- In 2017, CECs represented 71%, 84%, and 89% of total capacity bided in each round, respectively. Capacity oversubscription (2.67 kW, 2.93 kW, and 2.59 kW offered per kW tendered, respectively), paired with cost reductions (avg. clearing price 5.78 €ct./kWh, 4.29 €ct./kWh, and 3.82 €ct./kWh, respectively) - Since 2018, 60% of all rounds undersubscribed (0.8 kW avg. capacity offered per kW tendered). Low competition is insufficient to reduce costs (avg. strike prices between 5.9 and 6.3 €ct./kWh)	- All auction rounds but one have been oversubscribed (1.7 kW of avg. power capacity offered per kW tendered); support cost reductions (6.59 €ct./kWh strike price in first 2017 round, 5.97 €ct./kWh in 2020 round) - Weak citizen involvement: 2017 auction results included 32% of awarded projects pledging citizen financial participation; no awarded bidder opted for citizen co-investment in 2018 round	- 1st auction (2020) undersubscribed (0.85 MWh of capacity bided per MWh tendered) - Low level of competition, with an avg. strike price of 10.4 €ct./kWh for the 'community' preference category and 7.4 €ct./kWh for the remaining 'conventional' projects awarded – compared to a ceiling price of €ct.12/kWh

In France, successful bidders received a 3 €/MWh premium if local actors owned at least 40% of the joint-stock company or cooperative shares (with voting rights), and a 1 €/MWh premium if at least 10% of the project value was financed locally via equity or debt investment (CRE, 2020).[15] These measures are being reviewed and may be replaced by a multi-criteria, points-based ranking system whereby additional points can be granted to bids that pledge to include citizen investment (Énergie Partagée, 2020; Pié, 2021).

Finally, Ireland's first auction established a separate actor-specific category for projects with shared ownership (i.e., community-led projects),[16] along with two technology-driven categories. While community-led projects could bid in any category, if they competed only in the 'community' category, they benefited from pre-qualification exemptions (DECC, 2020a). However, in the next Irish auction the 'community' category will be reserved for projects that are fully owned by local communities, and a separate citizen investment scheme could be introduced (DECC, 2021a, 2021b).

2.2.4. Auction outcomes: level of competition and citizen participation

In Germany, while the first three onshore wind auctions in 2017 appear to have resulted in a high number of citizen-led projects, a high level of competition, and low average awarded support prices (Lundberg, 2019), the level of competition has decreased and remained low since the withdrawal of preferential conditions for CECs in 2018 (see Table 1). These conditions were terminated due to their alleged misuse by some developers, who maneuvered around legal definitions to benefit from preferential treatment when in fact their financial and operational structures were not representative of CECs (Gsänger and Karl, 2020). This resulted in the crowding out of community initiatives and a steep decline of citizen-driven projects (Gsänger and Karl, 2020; Sach et al., 2029). Since 2018, average awarded prices have remained high and competition levels low.

The French experience showcases a contrasting outcome, with only one undersubscribed onshore wind energy auction round. Relatively high levels of

[15] This included co-investments involving at least 20 individuals, or local authorities (i.e., municipalities).
[16] "Community-led projects" corresponded to projects at least 51% owned by a Renewable Energy Community, and where at least 51% of all profits, dividends, and surpluses thereby derived were returned to this entity (DECC, 2020a,b).

competition have been paired with declining support costs (see Table 1); this arguably occurring at the expense of a decline in citizen participation (Rüdinger, 2019). Finally, Ireland's first auction yielded a low level of competition, while fewer than 10% of awarded projects were community-led (Eirgrid, 2020).

3. Methodology

3.1. Methodological approach

This study uses a choice experiment to investigate the influence of key auction design elements on the decision of onshore wind energy project developers to participate in auctions, and to estimate their willingness-to-accept distinct auction-related risks. Choice experiments are rooted in discrete choice and random utility theory (Manski, 1977; McFadden, 1974), and have been widely used by scholars to elucidate the preferences of investors for clean energy investment (Petrovich et al., 2021; Salm and Wüstenhagen, 2018; Hille et al., 2018; Kubli et al., 2018; Salm et al., 2016; Menyeh, 2021). This approach assumes that objects can be decomposed into sets of attributes and attribute levels, and that each level is associated with a part-worth utility.[17] It also assumes that individuals aim to maximize the overall utility obtained from aggregating attribute-specific part-worth utilities (Lancaster, 1966; McFadden, 1980). Since preferences are investigated based on attributes and levels that are experimentally manipulated, researchers can elicit stated preferences for concepts beyond those observable on existing markets (Holmes et al., 2017; Louviere et al., 2000). This strategy is particularly suitable in this context as the historical data on citizen participation in RE auctions that is required to apply revealed-preference methods is limited. Choice experiments have also been applied to examine the effect policies have on investment decisions (Melliger and Lilliestam, 2021; Chassot et al., 2014; Lüthi and Wüstenhagen, 2012; Pons-Seres de Brauwer and Cohen, 2020), including in RE auction settings (Botta, 2019).

[17] Part-worth utilities are understood here as the levels of utility individuals impute to specific characteristics of objects (or attribute levels). The overall utility of an object corresponds thus to the sum of its part-worth utilities.

3.2. Survey structure

The questionnaire was created using Sawtooth Software's module SSI[18] and included four sections. First, respondents were asked a set of questions about their prior experience with RE auctions and factors influencing their bidding decisions. Second, they were introduced to the choice experiment and assigned a series of randomized choice tasks designed to elicit their preferences for hypothetical auction designs. Third, respondents were asked a set of questions aimed at investigating their experience with citizen participation and preferences for related support measures. Fourth, we collected socio-economic data about respondents (see Table A.1 in appendix). The survey was pretested with experts between February and April 2021 and improved based on their feedback prior to the start of the data collection.

3.3. Choice experiment design

The choice experiment comprised two parts. First, respondents were asked to imagine that they were planning to participate in a hypothetical auction hosted by a European country with a robust credit rating and comprehensive regulatory framework to obtain support for an onshore wind energy project. The introductory text provided a thorough description of the hypothetical auction scheme and project characteristics (see Figure A.1 in appendix). Second, respondents were presented with a series of choice tasks, each comprising three choice objects described by randomized levels of five attributes (see Table 2). Respondents were instructed to indicate the option their organisation would most likely opt for, assuming the former were real-life options. Alternatively, they could choose a "none" option if none of the choice objects disclosed in the choice tasks were sufficiently attractive. The use of a none option is generally recommended as it more accurately reflects real-life decision situations (Hill, 2017).

Attributes and levels were selected based on the results of a preliminary study. The latter included a literature review of the factors affecting auction-participation decisions, five semi-structured interviews with onshore wind energy project developers held between November 2020 and February 2021, expert consultations, and prior research conducted in the context of the EU-funded AURES II and MISTRAL-ITN projects.[19]

[18] https://sawtoothsoftware.com
[19] http://aures2project.eu/; https://mistral-itn.eu/. In particular, the AURES II online database of RE auctions in the EU (See: http://aures2project.eu/auct ion-database/; Status as of 30.04.2021).

Interviewees were provided with a list of potential attributes and asked to rank them according to their relative importance in relation to deciding whether to participate in auctions. The outcomes of this pre-study led to the identification of five auction attributes (see Table 2). The attributes and levels were designed to reflect the risk exposure various types of bidders face when participating in auctions, and to echo the policy trends described in Subsection 2.2. A symmetrical design was used to avoid the number-of-levels effect (Salm et al., 2016) – i.e., when attributes with more levels are associated with higher importance scores than those with fewer levels.

Table 2: Attributes and attribute levels manipulated in the choice experiment.

Attributes	Description	Attribute levels
Gross IRR	The expected annual financial return on investment before fees and taxes if the project is awarded support in the auction.	- 4% - 7% - 10%
Financial pre-qualification	The financial guarantee required to be able to participate in the auction. The guarantee is kept by the auctioning authority if the bid is successful at the auction, but the project is not realized.	- 5,000 €/MW - 30,000 €/MW - 70,000 €/MW
Mandatory share offer to local residents	The obligation to offer all citizens who have their permanent address within a 5 km radius of the project the opportunity to invest equity capital and own a minimum share (%) of the project with voting rights.	- 0% - 10% - 20%
Level of competition	The level of competition expected in the auction round. Defined as a function of the volume of power capacity tendered by the auctioning authority and expected aggregated volume of power capacity auction participants submitted in their bids to obtain support.	- Low level of competition - Medium level of competition - High level of competition
Realisation period	The amount of time successful bidders are granted to develop the project after winning the auction.	- 24 months - 36 months - 54 months

The gross internal rate of return ('*Gross IRR'*) attribute provided an indication of the annual return project developers could expect to make on their investment if their bid was successful in the auction and support was awarded. The Gross IRR included three levels – namely, 4%, 7%, and 10%. This design was chosen to elicit the broad range of returns respondents may require to be willing to accept changes in other attribute levels. The '*financial pre-qualification*' attribute represented the financial guarantee the auctioneer required for project developers to participate in the auction, and included three levels – namely, 5,000 €/MW, 30,000 €/MW, and 70,000 €/MW. These levels were selected to approximate minimum and maximum ranges defined in existing

national regulations based on the AURES II database of EU renewable energy auctions,[20] and to elicit a broad range of preferences.

The '*mandatory share offer to local residents*' attribute corresponded to the obligation of developers to offer all citizens whose permanent address is within a 5 km radius of the hypothetical onshore wind energy project the opportunity to invest equity capital and own a minimum share of the project, with voting rights. Three attribute levels were selected – namely, 0%, 10%, and 20%. Figure A.2 in appendix illustrates the capital structure of the hypothetical project that included the share offer to local citizens. In addition, complementary information about the conditions of the share offer was provided to respondents.[21]

The '*level of competition*' attribute was defined as specified in Subsection 2.1.2, and three levels were selected based on the auction outcomes presented in Subsection 2.2.4. A low level of competition referred to an auction that was expected to be 50% undersubscribed. A medium level of competition entailed an expected aggregated volume of power capacity submitted that was equal to the volume tendered in the auction. A high level of competition implied an auction that was oversubscribed by 50%. Further, the '*realisation period*' attribute represented the amount of time respondents were granted to develop the hypothetical project after winning the auction. Attribute levels were designed to reflect the range of realisation periods observed in different European markets, and included 24, 36, and 54 months.

Finally, the questionnaire included a total of ten randomized choice tasks. Figure 2 provides an example of a choice task as presented to respondents.

[20] http://aures2project.eu/auction-database/

[21] Respondents were informed that the share offer consisted of notifying all eligible parties in writing through at least one advertisement in a local newspaper, and a mandatory public hearing. Respondents were told that the share offer had to take place no earlier than two months before the planned commissioning of the first wind turbine. They were informed that if not all shares were subscribed to, their organisation could keep those that remained outstanding. Finally, respondents were told that failure to comply with regulations would result in loss of support.

Gross Internal Rate of Return (IRR)	4%	7%	10%	My organisation would not be interested in any of these options.
Financial pre-qualification	5 000 €/MW	5 000 €/MW	5 000 €/MW	
Mandatory share offer to local residents	10%	20%	0%	
Level of competition	Medium level of competition	High level of competition	Low level of competition	
Realisation period	54 months	36 months	24 months	
	○	○	○	○

Figure 2: Example of choice task used in the choice experiment. Source: Authors' elaboration generated with Sawtooth Software's module SSI Web.

3.4. Model specification and willingness-to-accept estimation

First, we estimated the relative preferences of project developers for different auction design elements – or part-worth utilities – by specifying a two-level Hierarchical Bayes (HB) model based on survey data using the Sawtooth Software. HB models are often used in such studies as they enable to address the potential lack of information at the individual respondent level by drawing information from other respondents. This makes this approach particularly relevant when the number of total observations is limited (Rao, 2014). At the lower level (individual respondent level), respondents are assumed to systematically select their preferred auction participation options based on their respective aggregated part-worth utilities. A multinomial logit model is used to specify the choice probability of individuals. At the upper level (across the population of respondents), a multivariate normal distribution comprising a means vector and covariances matrix is used to estimate the variation of individual part-worth utilities between respondents and to indicate the level of heterogeneity in the sample (Allenby et al., 2005; Orme and Howell, 2009).

The root likelihood (RLH) parameter is used to provide an indication of the quality of the HB model (Orme, 2016). A high RLH value denotes a good fit between the model and data, with RLH=1 indicating the best fit. In this study, the HB model is associated with an average RLH=0.72.[22] Given that respondents were presented with three auction participation options and one opt-out option per choice task, the null likelihood corresponds to 1/4=0.25 (Sawtooth Software, 2021). Since the RLH value associated

[22] The mean of all respondents' individual RLH values.

with the HB model is 2.88 times greater than the null likelihood value, the model is assumed to adequately fit the dataset (Hille et al., 2018).

Second, using part-worth utility results we computed aggregated willingness-to-accept (WTA) values following Salm and Wüstenhagen (2018). This allowed us to estimate the risk premium bidders would require to be willing to participate in auctions that include less preferred design elements. Results of the HB analysis can be found in Subsection 4.2, and WTA estimates in Subsection 4.3 and 4.4.

3.5. Data collection and sample

We identified potential respondents using a database that included 2,514 wind energy development companies,[23] contact lists, web searches, and relevant associations. We contacted a total of 370 potential respondents individually via email or direct messaging through a social media platform (LinkedIn) between April and June 2021. An initial message including information about the research project, data usage, and confidentiality was first sent out. A reminder was also sent in most cases, except when direct messaging via social media was used (as LinkedIn does not allow users to send multiple messages unless the initial one is accepted by recipients). Additionally, respondents were recruited through seven European and national RE associations that disseminated the survey among their members.[24] Survey responses were collected between April and July 2021.

One hundred and eighty-five respondents accessed the survey. After excluding incomplete responses, nine respondents who completed the survey but did not correspond to the target population were also removed from the sample. Insights from a total of 61 project developers who made an aggregated 559 experimental decisions are

[23] The database included 2,514 global wind energy development companies (status as of April 2021). Companies only active in the offshore wind energy sector or based outside the EU were excluded. Onshore wind energy companies that had developed (or had in development) more than five projects were selected for direct messaging (336 firms). Potential respondents were identified using personal networks, LinkedIn, and web searches. When no contact details could be found, or when project companies could be linked to other larger developers, the respective companies were excluded. The database can be found at:
https://www.thewindpower.net/store_actor_en.php?id_type=1.

[24] Large disseminators include four regional and national wind or RE associations who contacted a total of 427 members mainly via mailing lists, two citizen-led RE organisations who contacted 115 members via mailing lists and LinkedIn, and Strommarkttreffen.org, which has c. 5,000 members. Since not all members corresponded to our target group, the specific number of potential respondents reached through these disseminators is unknown. Large disseminators were thus excluded from the response rate calculations, as per Melliger and Lilliestam (2021).

thus included in the final sample, corresponding to a response rate of 16.5%.[25] Respondents took on average 18 min to complete the survey. The final sample contains seven partial survey responses where sufficient information was provided to permit their inclusion in the analysis. The sample size is limited by the small population of European onshore wind project development companies. Nevertheless, it is aligned with the sample size used in similar studies with professional investors (Lüthi and Wüstenhagen, 2012; Salm, 2018) and complies with recommendations from Orme (1998) regarding sample size requirements in choice experiments.

The final sample mainly consisted of men, on average in their mid-forties. This reflects the general under-representation of other gender identities in the RE sector (IRENA, 2019). Most project developers reported having at least 10 years of work experience. Further, 52% of respondents indicated that they worked for commercial project developers, and 30% for utility companies. Respondents affiliated with energy cooperatives represent 11% of the final sample. The sample includes representatives from 31 small and medium-sized enterprises (SMEs) – i.e., companies with up to 249 employees –, and 23 large companies. Finally, 56% of respondents reported being based in Germany or France, two of the largest European onshore wind markets. Additional information on socio-demographic data can be found in Table A.1 in the appendix.

4. Results and discussion

We first present descriptive results about respondents' prior RE investment experience, factors determining decisions to engage in RE auctions, and their preferred means to support citizen participation. This allows us to gain a better understanding of the investment process in the context of auctions. Based on the results of the choice experiment, we then present part-worth utility estimates and discuss the preferences of project developers for different auction design elements. Building on these findings, we finally present willingness-to-accept estimates for all project developers and explore differences between subgroups. This allows us to shed light on how and to what extent different auction design elements, particularly those aimed at increasing citizen participation, influence risk perceptions.

[25] Based on 370 potential respondents who were contacted via direct messaging (excluding large disseminators).

4.1. Descriptive results

The responses indicate that a considerable share of surveyed project developers (80%) had already participated in at least one auction round (see Figure A.3 in appendix), of which 94% reported winning at least one auction, underlining the quality of our sample. While 63% of these respondents reported having prior experience with onshore wind energy auctions, 47% revealed having prior auction experience in Germany, and 45% in France (see Figure A.4 and Figure A.5 in appendix). Interestingly, a large share of these respondents (49%) also claimed to have previously submitted bids that included, or pledged to include, citizen participation through equity or debt co-investment. Overall, 26% of respondents reported having experience with citizen co-investment as a general practice, 54% occasionally, and 20% reported no experience (N=54). Specifically, 37% of respondents indicated that their organisation tends to offer investment opportunities of between 1% and 10% of the overall project value, and 19% of respondents between 11% and 20% (see Figure A.6 in appendix). Finally, a minority of respondents (7%) indicated offering 51% of the project value or more.

Regarding factors shaping auction participation decisions, 23% of respondents ranked the type of remuneration scheme as the most important factor, while 20% ranked the pricing rule as the second most important factor (see Figure 3).[26] These results confirm earlier findings regarding the relative importance of price risk for RE investment (Egli, 2020).[27]

[26] We excluded the remuneration scheme and pricing rule from the choice experiment as these attributes are less relevant to our core research focus, namely measures to support citizen participation and actor diversity.
[27] This may be explained by the fact that specific pricing rules may incentivise strategic or low bidding (Polzin et al., 2019), resulting in additional uncertainty regarding the level of support developers may receive.

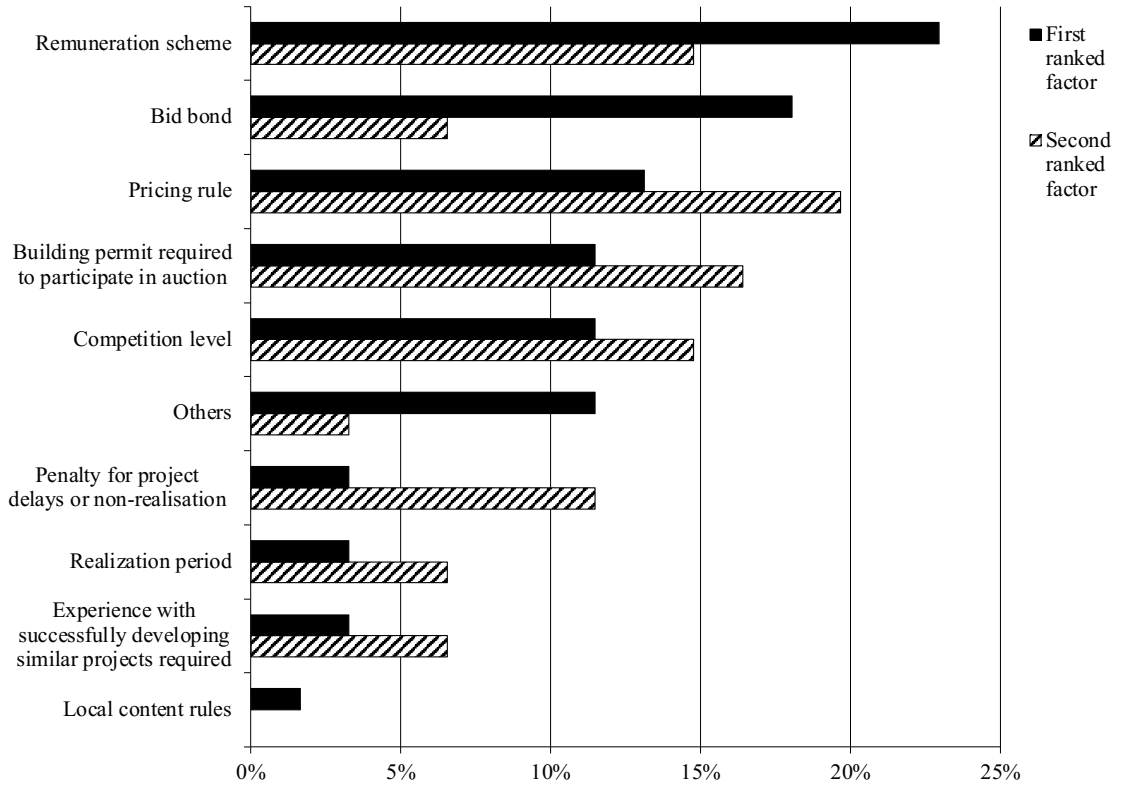


Figure 3: Factors with the greatest influence on the decision of project developers to participate in renewable energy auctions (one answer per factor possible, N=61).

Moreover, the preferred means of promoting citizen participation in projects subject to auction-allocated support appear to differ depending on developers' size. While two equivalent shares of SME respondents (each 19%) revealed that preferential conditions and a mandatory share offer to local residents were their preferred means of supporting citizen participation in auctions, 22% of large developers highlighted fiscal incentives as their favoured measure (see Figure 4). These insights suggest that SMEs tend to be more inclined to favour measures directly associated with auction schemes, while large project developers prefer indirect measures outside of auction settings. As mentioned in Subsection 2.1, SMEs may face greater barriers to auction participation than larger actors. The introduction of actor diversity measures may provide them with a competitive advantage over larger companies as they are likely to have stronger ties with local communities, facilitating thus the successful realisation of citizen participation initiatives.

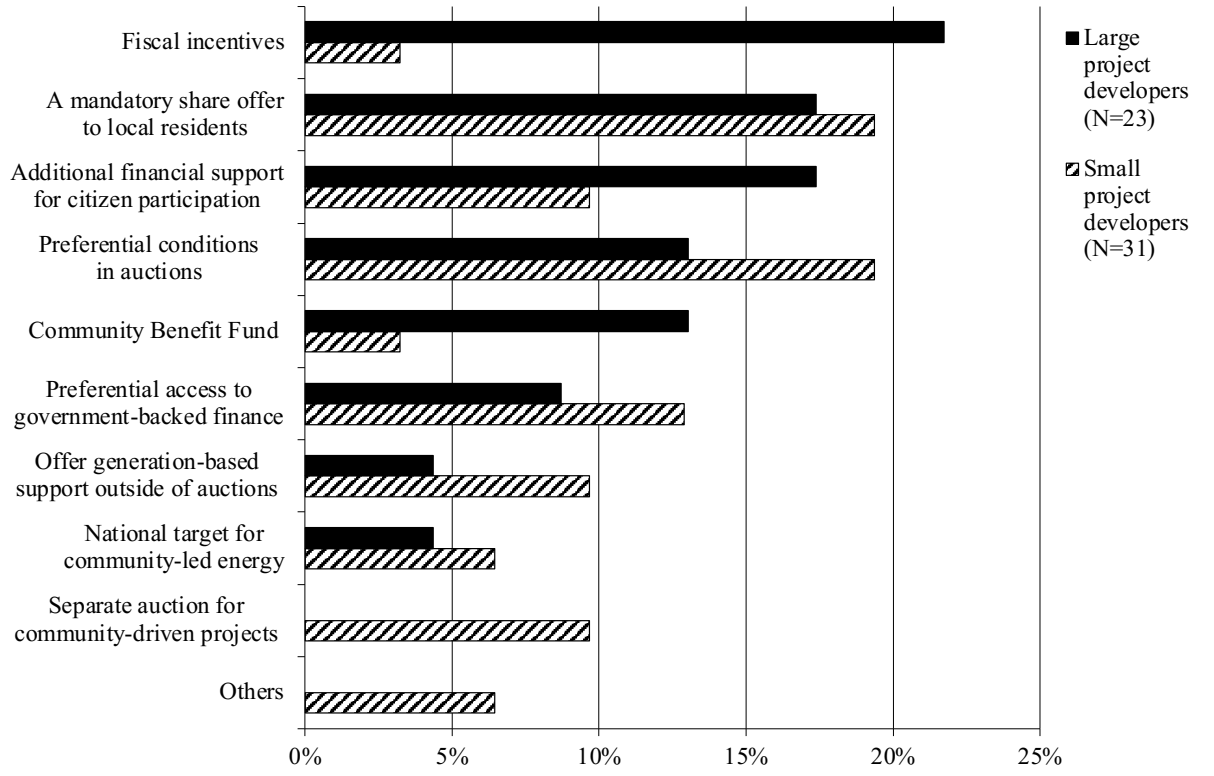


Figure 4: Preferred means of promoting citizen participation in projects subject to auction-allocated financial support (one answer possible, N=54).

Regarding citizen participation in RE projects in general (not specifically in the context of auctions), most respondents reported being open to some form of citizen participation, with a considerable share preferring financial participation through equity and/or debt investment (see Figure 5). Interestingly, both SMEs and large project developers revealed that public information events and financial participation through citizen equity investment were their preferred forms of citizen participation in RE projects. This insight is somewhat surprising since shared ownership is often associated with additional risk and costs for developers. Nevertheless, these results show that both SMEs and large project developers seem to be generally open to shared ownership.

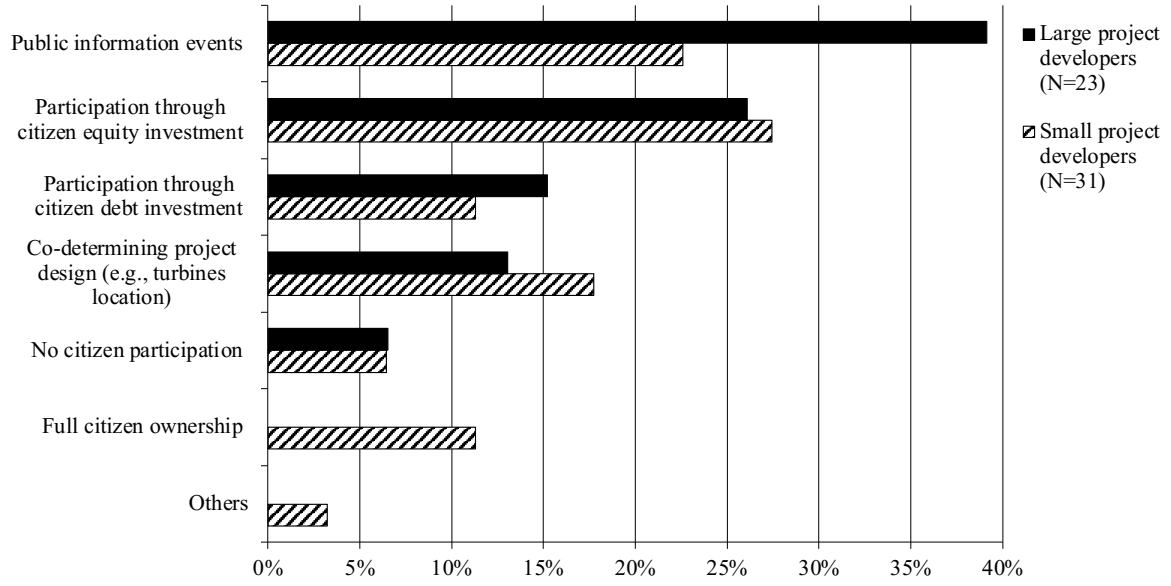


Figure 5: Preferred means of citizen participation in renewable energy projects (two answers possible, N=54).

4.2. Preferences for auction design elements

Part-worth utilities were estimated using the HB model as specified in Subsection 3.4 and zero-centred to facilitate within-attribute comparison. Table 3 presents the average zero-centred part-worth utility estimates, lower and upper 95% confidence intervals, and standard deviation (SD) values.

As expected, part-worth utility estimates show that respondents tend to prefer higher *Gross IRR* values (see Table 3). Regarding *financial pre-qualifications*, project developers appear to prefer a smaller financial guarantee. This insight supports the findings of prior studies that highlight the additional risk stringent guarantee requirements may generate for RE investors (Grashof, 2019). Indeed, we informed survey respondents that the auctioneer would keep the financial guarantee if the hypothetical project was not realized. Correspondingly, larger guarantees have the potential to become translated into higher penalties.

As for the *mandatory share offer to local residents*, results show that respondents tend to prefer no share offer requirement in the context of auctions. While this finding corroborates the overall preference of large developers for citizen participation measures operating outside the scope of auction schemes, these results are inconclusive with respect to SME responses, as this actor group overall prefers within-auction measures

(see Subsection 4.1). The relatively high SD estimates associated with these attribute levels indicate considerable variation among respondents (see Table 3). Additional HB analyses conducted separately with SMEs and large developers reveal that both actor groups have overall similar preferences with regard to the mandatory share offer attribute (see Table A.2 in appendix). However, the preferences of SMEs for different share offer levels vary considerably. Examination of individual-level preferences shows that all SMEs respondents who reported being affiliated with RE cooperatives preferred a 20% mandatory share offer. Despite other SME respondents also being inclined to favour some form of share offer, most exhibited strong preferences for no mandatory offer, indicating preference heterogeneity within this group.

Table 3: Results of the HB model for all project developers: Zero-centred utilities, lower and upper 95% confidence intervals, and standard deviations (N=61).

Attribute	Attribute levels	Zero-centred utilities	Lower and upper 95% confidence intervals	Standard deviations
Gross IRR	4%	-101.55	[-110.43; -92.66]	35.40
	7%	22.41	[16.35; 28.47]	24.15
	10%	79.14	[67.35; 90.92]	46.97
Financial pre-qualification	5 000 €/MW	23.18	[16.86; 29.50]	25.20
	30 000 €/MW	9.74	[5.42; 14.06]	17.23
	70 000 €/MW	-32.92	[-40.88; -24.96]	31.71
Mandatory share offer to local residents	0%	20.15	[9.36; 30.94]	42.99
	10%	0.34	[-4.83; 5.51]	20.60
	20%	-20.48	[-33.48; -7.49]	51.79
Level of competition	Low level of competition	21.23	[14.39; 28.06]	27.24
	Medium level of competition	12.29	[7.05; 17.53]	20.87
	High level of competition	-33.52	[-39.38; -27.66]	23.35
Realisation period	24 months	-29.89	[-36.01; -23.78]	24.37
	36 months	22.50	[17.40; 27.60]	20.32
	54 months	7.39	[-0.75; 15.54]	32.45
None-option	N/A	-1.08	[-30.29; 28.14]	116.43

As for the *level of competition*, results show the overall preference for a low level of competition as opposed to a medium or high level. As mentioned in Subsection 2.1, higher levels of competition increase allocation risk and reduce the probability of being awarded support. However, low levels of competition may increase bid prices and result in high costs for energy consumers and taxpayers. Regarding the *realisation period*,

respondents tend to prefer 36 months compared to 24 months or 54 months. A 36-month realisation period is typical in onshore wind auction designs across Europe, potentially explaining why respondents generally tend to prefer this timeframe. As explained in Subsection 2.1.4, a shorter realisation period may increase the perceived risk of incurring penalties if a project is delayed or not realized, and a longer period may be perceived as an opportunity for speculative behaviour.

Finally, an opt-out option was included for respondents to select when they judged that none of the choice alternatives were sufficiently attractive. The total share of choice tasks in relation to which respondents did not choose any of the auction-participation concepts (i.e., opted out) is 19.9% (N=61). Interestingly, large project developers chose to not participate in any auctions in only 11.3% of cases, while SMEs chose to opt-out in 25.8% of cases. This insight supports studies which suggest that smaller actors tend to face greater barriers to auction participation than larger ones (Grashof, 2019; Gsänger and Karl, 2020; Tews, 2018).

4.3. Willingness to accept

We computed aggregated WTA values to estimate the risk premiums respondents would require to be willing to participate in auctions that include less preferred design elements. Figure 6 shows the WTA results for all project developers. A WTA of zero indicates the most preferred attribute level. A positive WTA value represents the average additional risk premium respondents would require to participate in an auction that includes a less desirable design element instead of the preferred auction design, as specified in Subsection 4.2.

Results show that respondents are sensitive to the risk associated with *financial pre-qualification*, with the required risk premium increasing exponentially with higher bid bond levels. While moving from a bid bond valued at 5,000 €/MW to 30,000 €/MW is acceptable in exchange for an additional return of 0.43 percentage points, respondents are only willing to accept the highest level of this attribute (70,000 €/MW) for a premium of 1.79 percentage points (see Figure 6). These results show that respondents generally appear to be willing to participate in auctions for which a financial pre-qualification is required up to a certain threshold. The former also indicate the reluctance of most project developers to take on any allocation risk unless they are compensated for it, supporting

the findings of studies which show that this risk is perceived by bidders as being one of the most important ones associated with auctions (Đukan and Kitzing, 2021).

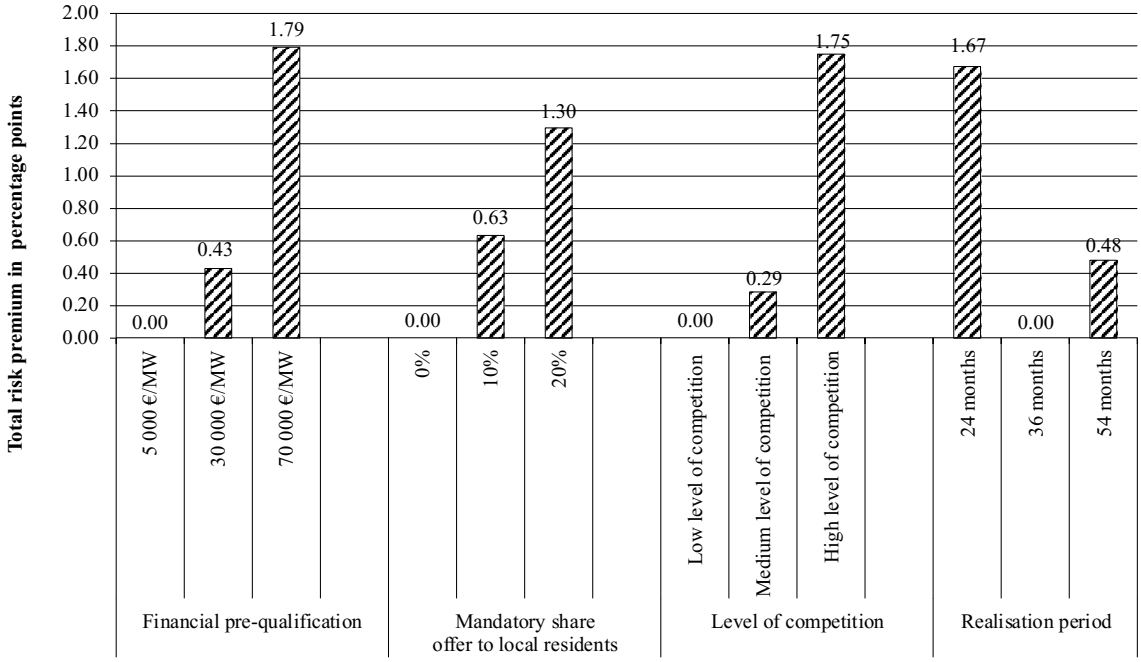


Figure 6: Willingness to accept results for all project developers (N=61).

As for the *level of competition*, the surveyed investors unsurprisingly prefer lower to higher levels of competition, and are only willing to participate in an oversubscribed auction in exchange for a risk premium of 1.75 percentage points.

When it comes to the *realisation period*, the picture that emerges is less clear. The preferred period is 36 months. Compared to this, a longer period of 54 months is the second-most preferred option, whereas the least preferred option is the shortest period included in our experiment. To move from 36 to only 24 months respondents require a risk premium of 1.67 percentage points. The non-linear distribution of part-worth utilities for this attribute illustrates that the professional investors in our sample have a shared understanding of the realistic timeline required from winning an auction to actually implementing a project. Speeding up this process may induce additional challenges, such as being under pressure to finalize negotiations with suppliers or address potential social acceptance issues. At the other end of the spectrum, an extended timeline is also perceived as creating additional risks for developers. This could be related to attracting participants who have not properly planned their projects, or because throughout the development process complications may arise in relation to suppliers and

other key stakeholders. This was also underlined by several of our pre-study interviewees.

Finally, regarding the attribute *mandatory share offer to local residents*, our findings show that while project developers may see value in citizen co-investment in general (see Subsection 4.1), they are also clearly aware of the risks involved. Accordingly, the risk premium increases almost linearly with the share of capital that needs to be offered. To move from no required participation to offering one-fifth of capital to local residents, respondents would ask for a risk premium of 1.30 percentage points.

4.4. Differences in willingness to accept between large and small project developers

In the final step, we conducted a segmentation analysis to explore differences in willingness to accept between different investor types. For this, we split the sample by firm size, calculating WTA separately for respondents working for large developers and SMEs (see Subsection 3.5 for information on subgrouping). Results are presented in Figure 7.

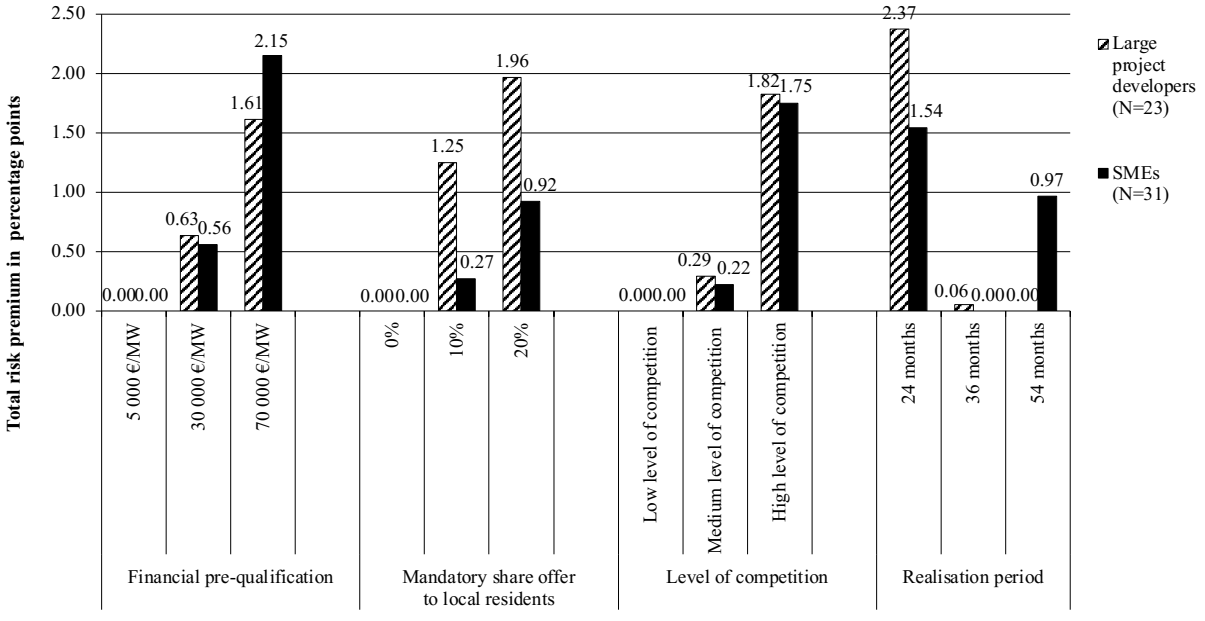


Figure 7: Differentiated willingness-to-accept results for SMEs and large project developers (N=54).

We find that, apart from the *level of competition* where few differences between SMEs and large developers are observed, some interesting nuances emerge in relation to the other attributes. When it comes to *financial pre-qualification*, SMEs are more sensitive to high levels of this attribute than large developers. This situation may be driven by two factors: On the one hand, 70,000 €/MW represents a more significant amount of money for a small organisation than a large organisation, potentially representing a greater barrier to auction participation. On the other hand, large developers may be better able to diversify the risk of losing a bid bond by pursuing a larger portfolio of projects, as suggested in Subsection 2.1.1.

With regard to the *realisation period*, SMEs follow the pattern described in Subsection 4.3, preferring 36 months over both shorter and longer timelines. While large developers are almost indifferent in terms of the choice between 36 and 54 months, they are more sensitive to shorter implementation periods than SMEs. This may reflect the fact that smaller developers tend to be more agile, whereas respondents working in large firms are painfully aware of the challenges involved in speeding up processes within their organisations (Hockerts and Wüstenhagen, 2010). As such, they may be cognizant of the fact that they have less of a relative advantage over their smaller competitors in settings when moving swiftly is required.

The largest difference between both groups occurs with regard to the attribute *mandatory share offer to citizens*, where it is again the larger firms that are about twice as risk averse as their smaller competitors. Interestingly, that difference is even more pronounced at the medium level of this attribute. Offering 10% of capital to local residents is something that SMEs tend to be relatively comfortable with, possibly reflecting their greater ability to interact with local stakeholders.

5. Conclusions and policy implications

This study investigated how the design of renewable energy (RE) auctions influences the risk perceptions of project developers. Auctions were initially introduced with a focus on lowering the cost of RE policy support, but decision-makers are increasingly aware that effective policies involve meeting a broader set of objectives, including increasing actor diversity and social acceptance. The introduction of auction design elements intended to achieve those objectives has led to mixed results. Our study generates novel and fine-grained empirical insights about developers' perceptions of

those auction design elements and the implications for their assessment of risk-adjusted returns.

Based on 559 experimental investment choices made by 61 European onshore wind energy developers, we find that professional investors are sensitive to a number of risks embedded in auction designs, and that they are only willing to accept an increase in the level of those risks when remuneration from the auction represents sufficient compensation. Our findings serve as a reminder that, in some respects, the interests of project developers and policymakers are in clear contrast to each other. For example, while policymakers seek to minimize cost and increase competition, project developers prefer projects with greater profitability along with predictable and stable returns, and tend to be less willing to accept auction settings that involve high levels of competition. An average risk premium of 1.75 percentage points would be required by developers to participate in an oversubscribed auction instead of an undersubscribed one.

While policymakers cannot simply design auctions based on maximizing the utility of RE investors, there are certain design elements in relation to which taking the experience of developers into account may be desirable. For example, when it comes to the required implementation period of projects winning an auction, our survey respondents on average preferred a period of 36 months and tended to be sensitive to the risks involved with both shorter and longer time horizons. Therefore, well-meaning policymakers who think longer project realisation periods will encourage investor diversity should be mindful that this only works to an extent, as very long realisation periods are perceived to increase rather than decrease risk. We also found differences between investor types: SMEs would require an average risk premium of 0.97 percentage points to move from an auction with a 36-month realisation period to one with 54 months. In contrast, project developers, especially larger ones, would also require a considerable risk premium to accept a shorter realisation period. A mid-range design is thus overall preferred. One area where actor diversity may benefit from policy differentiation is financial pre-qualification. Our results show that project developers are generally willing to accept the requirement to submit a bid bond up to a certain threshold, with smaller players reacting more sensitively than larger ones. This provides empirical support for policymakers who have decided to offer preferential conditions to smaller actors in relation to this particular design element.

As for auction design elements that facilitate citizen co-investment, our results shows that while developers may be generally open to co-investment, they are also clearly

aware of the risks implied by it. The required risk premium increases with the share of capital that needs to be offered to local residents. Offering 20% of capital to residents implies a risk premium of 1.3 percentage points for the overall sample, and this premium is about twice as large among large developers than for SMEs. In general, the value of citizen co-investment, especially at medium levels (such as 10% of capital offered to local residents), seems to be more appreciated among SMEs than larger players, possibly because of their superior ability to interact with local stakeholders.

Based on these insights, three policy implications become clear. First, since moderate financial pre-qualifications do not appear to significantly increase risk premiums, policymakers may want to promote their use in auction settings to ensure timely project realisation. Second, shorter realisation periods are one of the factors driving the largest increase in implied risk premiums, especially for larger project developers. This may reflect the current acceptance and permitting issues observed in many major European markets. By adapting permitting regimes through institutional capacity building and creating "one-stop shops", national permitting authorities could shorten realisation periods and reduce risk premiums – a proposition already highlighted by some industry stakeholders to accelerate the energy transition (Richard, 2021; WindEurope, 2020). Third, our results serve as a reminder that auctions are not a panacea for delivering on a broad variety of policy objectives beyond cost effectiveness, and that promoting actor diversity in this context comes at a price. While our study has highlighted important nuances that may help improve current auction designs, auctions are not a one-size-fits-all solution to the multiple objectives pursued by energy policies. In particular, the results of this study point towards the apparent trade-off between building in elements that maximize citizen co-investment on one hand, and creating low-cost projects on the other. Policymakers unwilling to compensate project developers for the risks and complexities associated with involving local residents through financial participation will either have to find other ways to promote actor diversity and social acceptance, or may be faced with failure to achieve their RE policy objectives. In this respect, policymakers could consider introducing more ample exemptions from auction participation for community-based and/or citizen-driven business models.

This study has limitations that pave the way for future research. While design elements aimed at encouraging citizen participation in RE projects may increase social acceptance, further research is needed to better understand the threshold at which improvements in local community acceptance are outweighed by decreases in cost effectiveness in auction settings. This could contribute to a more refined understanding

of the trade-offs that policymakers will have to acknowledge when assessing the suitability of auctions for achieving a multitude of policy objectives, including fostering actor diversity and local acceptance. This study provides exploratory evidence of how different auction designs influence risk perceptions. Future research could build on these findings using qualitative methods such as focus groups to further explore developers' attitudes and perceptions, particularly regarding the shared ownership risk. It could also investigate the effect of increasing levels of competition on citizen participation, including in the context of a mandatory share offer. Once sufficient data on citizen participation in the context of auctions become available, our stated preference analysis could be complemented with revealed preference methods. Finally, future research could explore the impact of other actor diversity measures on the risk perceptions of bidders (e.g., multi-criteria auctions).

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Disclaimer

The results and conclusions in this publication reflect only the author’s view. The European Commission is not responsible for any use that may be made of the information it contains.

Appendix

Table A.1: Socio-demographic results.

Variable	Value	%
Gender identity (N=54)	Women	11%
	Men	80%
	Non-binary	2%
	Rather not say	7%
Age (N=54)	Average	43
Work experience (N=54)	Less than 5 years	7%
	5 to 9 years	17%
	10 to 14 years	24%
	15 to 19 years	24%
	20 to 25 years	7%
	More than 25 years	20%
Industry specification (N=61)	Multinational utility company	28%
	Local/regional utility company	2%
	Multinational commercial project developer	31%
	Local/regional commercial project developer	21%
	Energy cooperative	11%
	Other	7%
Company size (N=54)	1 to 9	24%
	10 to 49	13%
	50 to 249	20%
	250 and more	43%
Working country (N=54)	Austria	4%
	Belgium	7%
	Croatia	7%
	Denmark	7%
	France	17%
	Germany	39%
	Italy	4%
	Spain	2%
	Switzerland	4%
	United Kingdom	4%
	Others	6%

Introduction

In the upcoming section, you will be asked to choose from different **options to participate in a wind energy auction.** These options are based on several characteristics shown in the table below. Please read the following explanations carefully to fully understand the characteristics used in the upcoming interactive section.

Imagine you want to participate in an **auction hosted by a European country** with a robust credit rating (AA or higher) and comprehensive regulatory framework, **to obtain support for an onshore wind project (i.e. 15 MW installed capacity, 30% capacity factor).** Characteristics of the auction are:

- **Technology-specific** (onshore wind only)
- **'Pay-as-bid'** (awarded bidders are paid the bid price they submit)
- **Two-sided contract-for-difference** for **20 years** (you must return the upside when the electricity price is above the bid level, and receive support when it is below)
- **Building permit required**
- The same rules apply to **all** bidders.

Please read the explanations below carefully to understand the categories used in the following interactive section. You can re-visit these definitions at any time in the upcoming section by scrolling your pointer over each category.

Figure A.1: Introductory text of the choice experiment with description of the hypothetical auction scheme and project characteristics (Note: the table referred to in this text corresponds to Table 2). Source: Authors' elaboration generated with Sawtooth Software's module SSI Web.

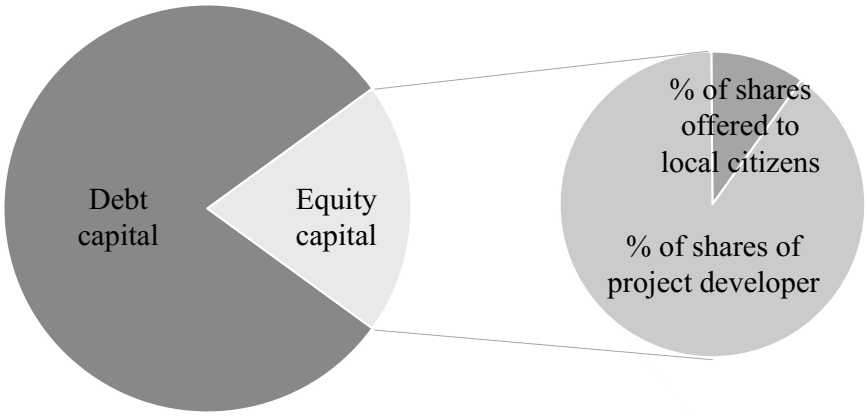


Figure A.2: Example of capital structure associated with the mandatory share offer to local residents attribute, as disclosed to survey respondents.

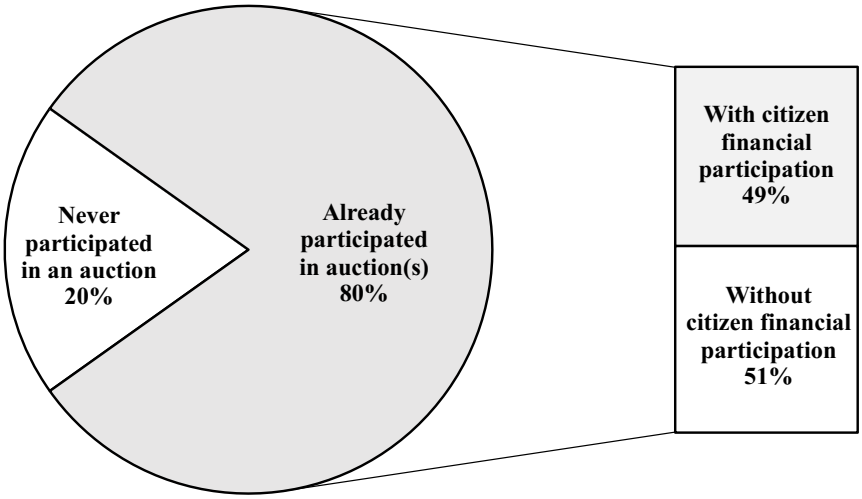


Figure A.3: Previous experience of project developers with participation in renewable energy auctions and the inclusion of citizen investment (N=61).

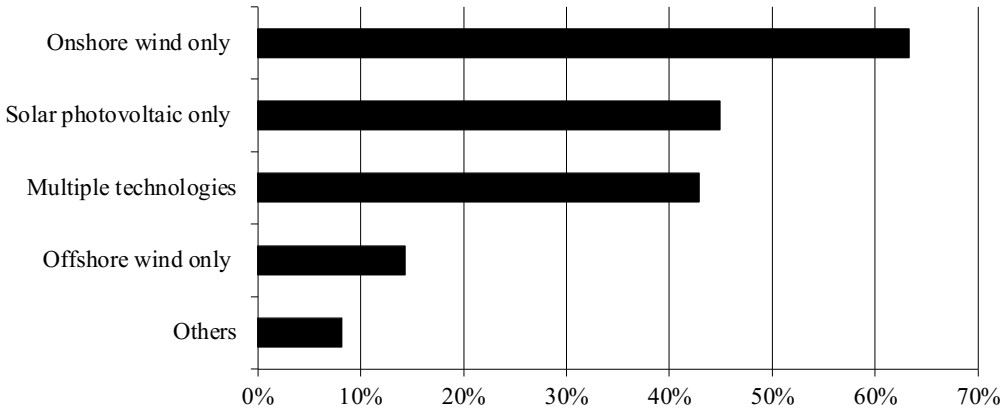


Figure A.4: Types of renewable energy auction project developers had previously participated in (multiple answers possible, N=49).

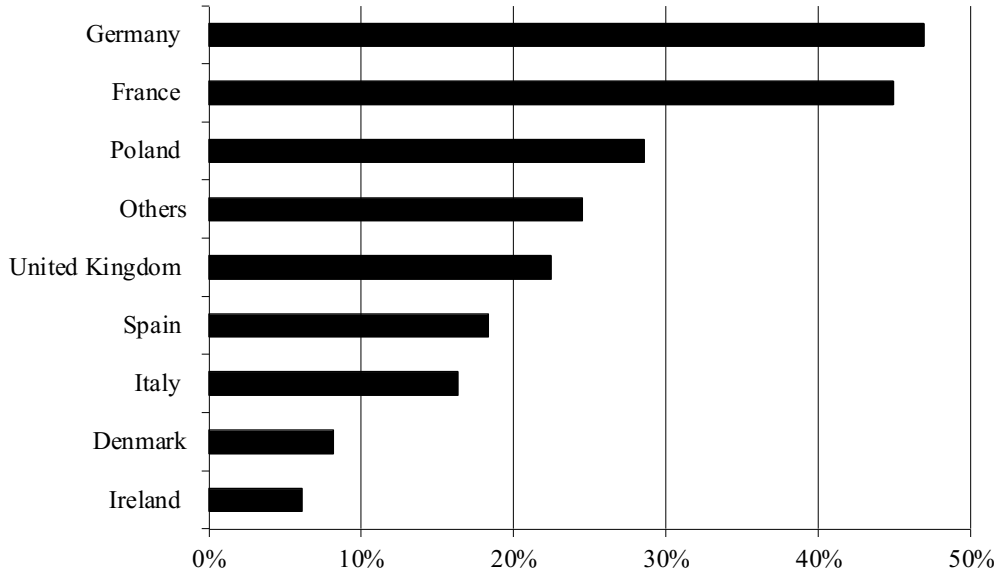


Figure A.5: Countries in which project developers had previously participated in renewable energy auctions (multiple answers possible, N=49).

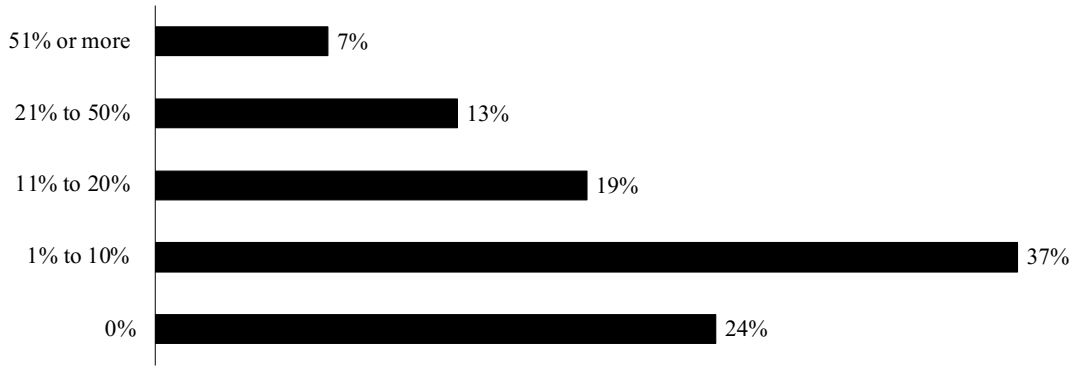


Figure A.6: Typical share of project ownership or revenue developers offer to citizens (one answer possible, N=54).

Table A.2: Results of the HB model for SMEs and large developers: Zero-centred utilities, lower and upper 95% confidence intervals, and standard deviations (N=54).

		HB model small and medium-sized enterprises (N=31)			HB model large project developers (N=23)		
Attribute	**Attribute levels**	**Zero-centred utilities**	**Lower and upper 95% confidence interval**	**Standard deviations**	**Zero-centred utilities**	**Lower and upper 95% confidence interval**	**Standard deviations**
Gross IRR	4%	-97.74	[-110.90;-84.58]	37.37	-97.76	[-108.43;-87.08]	26.13
	7%	18.06	[9.01;27.11]	25.71	19.18	[9.62;28.74]	23.40
	10%	79.68	[61.36;98.01]	52.05	78.58	[63.89;93.27]	35.94
Financial pre-qualification	5 000 €/MW	26.73	[18.76;34.71]	22.67	22.01	[9.20;34.82]	31.34
	30 000 €/MW	10.16	[5.40;14.91]	13.51	3.39	[-6.69;13.46]	24.66
	70 000 €/MW	-36.89	[-46.72;-27.07]	27.92	-25.40	[-41.60;-9.19]	39.64
Mandatory share offer to local residents	0%	11.79	[-4.43;28.01]	46.08	31.46	[19.96;42.95]	28.12
	10%	3.69	[-2.72;10.10]	18.21	-5.19	[-16.28;5.91]	27.16
	20%	-15.48	[-34.93;3.96]	55.23	-26.27	[-40.91;-11.64]	35.81
Level of competition	Low level of competition	19.42	[7.79;31.06]	33.05	20.71	[10.97;30.45]	23.83
	Medium level of competition	12.93	[7.37;18.48]	15.79	12.17	[0.46;23.89]	28.66
	High level of competition	-32.35	[-44.69;-20.01]	35.05	-32.88	[-40.82;-24.95]	19.42
Realisation period	24 months	-20.92	[-31.70;-10.13]	30.63	-45.95	[-51.45;-40.46]	13.45
	36 months	24.77	[17.27;32.27]	21.30	22.15	[11.68;32.63]	25.63
	54 months	-3.85	[-14.77;7.06]	31.00	23.80	[12.04;35.57]	28.79

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Paper II. Risk-adjusted preferences of utility companies and institutional investors for battery storage and green hydrogen investment[28]

Elizabeth Côté[29,]*, *Sarah Salm*[30]

Abstract

Achieving climate-neutrality requires considerable investment in energy storage systems (ESS) to integrate variable renewable energy sources into the grid. However, investments into ESS are often unprofitable, in particular for grid-scale battery storage and green hydrogen technologies, prompting many actors to call for policy intervention. This study investigates investor-specific risk-return preferences for ESS investment and derives policy recommendations. Insights are drawn from 1,605 experimental investment-related decisions obtained from 42 high-level institutional investors and utility representatives. Results reveal that both investor groups view revenue stacking as key to making ESS investment viable. While the expected return on investment is the most important project characteristic, risk-return preferences for other features diverge between groups. Institutional investors appear more open to exploring new technological ventures (20% of utility respondents would not consider making investments into solar photovoltaic-hydrogen), whereas utilities seem to prefer greenfield projects (23% of surveyed institutional investors rejected such projects). Interestingly, both groups show strong aversion towards energy market price risk. Institutional investors require a premium of 6.87 percentage points and utilities 5.54 percentage points for moving from a position of fully hedged against market price risk to a scenario where only 20% of revenue is fixed, underlining the need for policy support.

Keywords: Choice experiment, Energy storage, Grid-scale battery, Green hydrogen, Investment decision, Energy policy.

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1. Introduction

Achieving climate-neutrality by 2050 requires considerable clean energy investment. This vision pursued by the European Commission and more than 110 countries is in line with the Paris Agreement objective of limiting the rise in global temperature to "well below 2°C" compared to pre-industrial levels, preferably to 1.5°C (EC, 2018; UN, 2020). The European Green Deal articulates a roadmap for making Europe the first carbon-neutral continent (EC, 2019). Its implementation relies on scaling up sustainable investment and is enabled through a new taxonomy (EC, 2020). Reaching a state of carbon-neutrality by 2050 could require up to USD 130 trillion in clean energy investment globally (BloombergNEF, 2020a). Such investment could accelerate the growth in variable renewable energy sources (RES) from 9% of global power generation today to at least 75% (BloombergNEF, 2020a; IEA, 2020a). A considerable share of this expenditure is also required to deploy supporting infrastructure like energy storage systems (ESS) to facilitate RES integration (IEA, 2020b).

ESS are expected to play an important role in decarbonization as growing shares of variable RES challenge the reliability of power systems (Arbabzadeh et al., 2019; Blanco and Faaij, 2018; Zsiborács et al., 2019). RES provide several benefits compared to incumbent energy sources – e.g., lower carbon emissions, new employment opportunities, and enhanced public health (IRENA, 2017). However, some characteristics of RES such as the variable and unsynchronized power output, uncertain resource availability, spatial constraints regarding resource quality, and decentralisation can jeopardize the quality, flow, stability, and balance of power systems (Sinsel et al., 2020). A broad range of ESS technologies is available to address these issues. Given the versatility of grid-scale battery storage and potential role that hydrogen could play in addressing the seasonal mismatch between RES generation and power demand, these technologies are foreseen by some actors as key components of a clean energy future (Capros et al., 2019; IEA, 2020c). Their role is expected to be determinant in relation to the achievement of climate goals; in particular, for the abatement of the final shares of carbon emissions (Victoria et al., 2019), thus requiring considerable investment.

One stream of academic literature that investigates ESS investment focuses on asset valuation, with studies differentiating in terms of technologies and applications (Gaudard and Madani, 2019; Kelly and Leahy, 2020; Sioshansi et al., 2011; Yu and Foggo, 2017). While mature technologies such as pumped hydro are sometime found to offer good business cases to investors, investments in less mature technologies like

hydrogen production and storage are often found to be unprofitable (Baumgarte et al., 2020). This has prompted many scholars and industry actors to call for governmental intervention through policy support and market development to mitigate risks for investors (BloombergNEF, 2020b; Martins and Miles, 2021; Nikolaidis and Poullikkas, 2017; Vorushylo et al., 2016). Since professional investors could play an important role in financing ESS (Huang et al., 2020), understanding the risk-return preferences of this heterogeneous group is crucial for mobilizing their full investment potential.

Only a few scholars have investigated the risk-return trade-offs of private investors in the context of ESS investment (Krömer, 2019; Krömer and Gatzert, 2018). Salm and Wüstenhagen (2018) analysed the preferences of incumbent energy firms and pension funds for pumped hydro storage investment. Their study suggests that investor-specific policies could contribute to lowering the financing cost of such assets. Historically, both utility companies and institutional investors[31] have a track record in financing clean energy infrastructure (Helms, 2016; IEA, 2020d). Institutional investors have the potential to play an important role in early-stage capital recycling, which is crucial to reducing the cost of capital of assets and enabling new investment (McInerney and Bunn, 2019). While Salm and Wüstenhagen (2018) note that the preferences of utilities and institutional investors for project characteristics are likely to differ, little is understood about these differences in relation to other ESS investment. Since policies may play a major role in rendering ESS business cases viable by mitigating risks for investors, there is a need to obtain a better understanding of what kind of support would be required by different types of investors to facilitate the deployment of key ESS technologies such as battery storage and hydrogen production and storage.

This issue is addressed here by drawing empirical insights from a choice experiment conducted with 42 high-level institutional investors and representatives from utility companies who undertook an aggregated 1,605 investment-related decisions. The objective is to investigate and quantify the willingness of these two investor groups to finance ESS assets in the German market, where growing shares of variable RES is resulting in increasing flexibility requirements (Jankowska et al., 2020). This study also seeks to shed light on, inter alia, prior ESS investment experience, perceived barriers, and expected revenue streams. We are particularly interested in investigating the

[31] By institutional investors, we understand profit-oriented entities that pool money from their clients to purchase securities, real property, or assets, or to make loans (based on IRENA, 2020b). Our survey sets the focus on those interested in direct long-term equity investments in projects rather than companies (not indirect via funds).

preferences of these two investor groups as, although they are both investing long-term equity in clean energy assets, their core business largely differs. While the core expertise and resources of utility companies lies in energy-related business cases, institutional investors invest also across other sectors. Further, utility companies tend to prioritize investments that provide them with strategic advantages, whereas institutional investors – e.g., pension funds, insurance companies, or investment funds which pool capital from several actors – may particularly aim at achieving the returns necessary to meet their liabilities towards their clients (Hamilton and Zindler, 2016). Differences in terms of goals, motivations, and resources may result in different risk perceptions and return expectations for ESS investment. This work contributes thus to the academic literature that investigates investment preferences for ESS assets. The findings may provide guidance for the design of investor-specific policies for further developing the ESS investor ecosystem.

The following section presents background information pertinent to the analysis. Section 3 details the methodology that was used. Section 4 reports and discusses the survey and choice experiment results. Section 5 concludes by summarizing key findings and highlighting policy implications, limitations, and suggestions for further research.

2. Background

As energy storage technologies are relatively scarcely addressed in the energy investment research, this section first provides information on key grid-scale ESS technologies and recent developments. The focus is on Germany since the country recently emerged as a global leading market for energy storage (IEA, 2020e). The German government also recently proposed an ambitious strategy to prompt the deployment of hydrogen assets (BMWi, 2020a). This background information serves as input to the subsequent analysis and discussion.

2.1. Identifying key grid-scale energy storage technologies

Various ESS technologies offering distinct specifications are available to address different needs. The suitability of technologies in relation to specific applications vary based on their response time, discharge duration, and power capacity (Baumgarte et al.,

2020).[32] Table 1 shows examples of services ESS could provide to support the integration of variable RES. High-capacity flywheels and supercapacitors can provide a rapid response, making them well suited to frequency regulation services. However, relatively brief discharge times limit their use to short-term applications (Ibrahim et al., 2008). Pumped hydro storage (PHS) and compressed air energy storage (CAES) have a medium-to-long discharge duration and relatively large power capacities, making them fit for services such as time-shifting. PHS is mature, widely used, and suitable for a variety of applications (Connolly et al., 2011; Egerer and Schill, 2014; Karhinen and Huuki, 2019; Ming et al., 2013; Steffen and Weber, 2013). However, deployment is limited to locations where multiple water elevations are available (Blanco and Faaij, 2018). Diabatic CAES[33] is an economically viable alternative to PHS. However, carbon emissions from the use of natural gas in discharging cycles raise questions about its sustainability (Boffino et al., 2019). Adiabatic CAES could be a clean substitute, but higher costs hinder investment (Hammann et al., 2017).

Grid-scale batteries, in particular lithium-ion (Li) batteries, have recently emerged as key components of future energy systems, thanks to their short response time, medium discharge duration, and power capacity, making them suitable for a broad range of applications (Baumgarte et al., 2020; IEC, 2012). Batteries have historically been used to provide grid and ancillary services but applications are now diversifying (IEA, 2020f). Hydrogen technologies are also attracting attention due to their potential role in providing versatile power storage services and facilitating sector coupling (Capros et al., 2019). Although hydrogen technologies have a relatively low round-trip efficiency, their long discharge duration and potentially large capacity could offer a low-carbon solution to the problem posed by the seasonal mismatch between RES generation and energy demand. This energy carrier could also contribute to broadening decarbonization efforts beyond power generation to sectors such as industry, transport, and buildings (Petkov and Gabrielli, 2020). Subsections 2.2 and 2.3 provide further information on these two key ESS which are the focus of this research endeavour.

[32] Response time is understood as the speed of reaction; discharge duration as the time for which a system at full capacity can provide power; and power capacity as the maximal amount of power stored or supplied.
[33] A diabatic CAES process involves a transfer of heat generated through the combustion of natural gas that results in the release of carbon dioxide. In contrast, an adiabatic CAES process does not rely on natural gas but alternatively uses heat generated in the compression phase (Boffino et al., 2019; Hammann et al., 2017).

Table 1: Typical grid-scale ESS services for supporting RES integration into power systems. Source: IEC, 2012 (pp. 77–78).[34]

	Service	Discharge duration	Description	ESS technology examples
Load-shifting	Time-shifting, Arbitrage, Load levelling	Hours to days	Power stored during low-demand periods and released at peak demand. Solves the mismatch between diurnal generation cycles and load cycles.	Batteries, CAES, PHS
	Seasonal-shifting	Months	Energy generated during the time of the year when RES output is high is stored for months and released when RES output is low and energy demand high. Enables low-carbon energy provision year-round.	Hydrogen
	Load following, Ramping control	Minutes to hours	Power storage of excess RES output, and release based on hourly-changing demand. Addresses the variability of RES during periods of critical load (peaks). Ensured through the provision of ancillary service or fast energy market.	Batteries, flywheels, PHS, CAES
Ancillary services	Power quality and stability – e.g., voltage support	< 1 second	Supply of reactive power to address voltage variation. Solves instability and harmonic-related issues with voltage due to uncontrollable variable RES.	Batteries, flywheels
	Frequency regulation	Seconds to minutes	Fast-response increment or decline in power output to stabilize frequency. Addresses variability of RES output.	Batteries, flywheels, PHS
	Spinning reserves	~10 Minutes	Fast-response increment or decline in power output to address a contingency such as a generator failure.	PHS, flywheels, Batteries
	Supplemental or non-spinning reserves	Minutes to hours	Response resource that is activated to replace a spinning reserve. Provides power reliability in the case of a long-lasting RES output drop.	PHS
	Emergency power supply, Black start capacity	Minutes to hours	Re-starts power systems in case of failure.	Batteries
Others	Efficient use of transmission network	Minutes to hours	Supports grip-operator with time-shifting and other operating services to defer the need for upgrades in transmission system. Reduces costs and addresses spatial constraints on RES resource quality.	Batteries
	Off-grid support	Seconds to hours	Supports the integration of RES into small power grids through time-shifting and power-quality applications (e.g., island system).	Batteries

[34] Different battery types are used for various applications – e.g., lead acid (LA), lithium-ion (Li-ion), sodium sulphur (NaS) and redox flow batteries. See IEC, 2012 (pp. 77–78) for further information on specific applications.

2.2. Recent developments concerning battery and hydrogen storage

Grid-scale batteries attracted an annual global investment volume of nearly USD 2 billion in 2019 (IEA, 2020d). Li-batteries dominate grid-scale applications, probably due to the 89% price decline observed between 2010 and 2020 (BloombergNEF, 2020c). The average market price of Li-battery packs is expected to continue to fall, from USD 137/kilowatt-hour (kWh) today to nearly USD 100/kWh by 2023 (BloombergNEF, 2020c). The technology offers a good trade-off in terms of energy density, cost, and market readiness (Faunce et al., 2018). As a result, the global cumulative grid-scale battery storage installed capacity, which reached 10 GW in 2017, is expected to continue to grow, with Li-batteries playing a dominant role (IRENA, 2019).

Hydrogen can be produced and stored using various technologies.[35] The debate among scholars and practitioners about the role hydrogen could play in the energy transition typically revolves around the feedstocks and energy sources used in the generation processes.[36] Green hydrogen from water electrolysis using RES is seen as the cleanest energy carrier (Nikolaidis and Poullikkas, 2017). In 2019, the global annual capacity of hydrogen electrolysers reached a record 25 MW of electricity input (MW_e), corresponding to nearly USD 40 million in capital expenditure (IEA, 2020d). This represents a sharp increase from the 2 MW_e observed in 2010. Hydrogen is most commonly stored as compressed gas in pressurized tanks (Nikolaidis and Poullikkas, 2017; Widera, 2020). Underground storage in geological formations such as salt caverns represents a promising low-cost alternative for large-scale storage, with Germany having the highest storage potential in Europe (Caglayan et al., 2020). However, this technology is at an early stage of development (Lankof and Tarkowski, 2020; Liu et al., 2020).

While the price of electrolyser-made hydrogen is currently higher than for hydrogen made from other manufacturing methods, the cost of alkaline electrolysers manufactured in North America and Europe fell by 40% between 2014 and 2019 (BloombergNEF,

[35] Nikolaidis and Poullikkas (2017) discuss 14 hydrogen production methods, and Hirscher et al. (2020) provide an overview of recent hydrogen storage developments.

[36] Colour coding is commonly used to refer to different conversion paths. For example, grey, brown, or black hydrogen is produced using fossil fuels and is associated with high levels of greenhouse gas (GHG) emissions. Blue hydrogen combines the use of fossil fuels with carbon capture and storage to mitigate GHG emissions. Turquoise hydrogen is produced through the pyrolysis of fossil fuels and creates solid carbon as a by-product. Green hydrogen is mainly produced using electrolysers and RES. Yellow or purple hydrogen use electrolysers and nuclear power (Noussan et al., 2020).

2020b).[37] This decrease can be attributed to the scaling up of system capacities (IEA, 2020d). Alkaline electrolysers dominate grid-scale installations, but a shift towards polymer electrolyte membrane (PEM) electrolysers has recently been observed as this technology offers greater operational flexibility, making it better suited for intermittent RES (IEA, 2020g; Schmidt et al., 2017). If electrolyser costs continue to fall through the scaling up of manufacturing activities, green hydrogen could be produced at a levelized cost ranging from USD 0.7/kg to USD 1.6/kg in most regions by 2050, a sharp decrease from the nearly USD 2.5/kg to USD 4.5/kg observed today (BloombergNEF, 2020b). This could make this energy carrier cheaper on an energy-equivalent basis than some incumbent fuels,[38] as well as cheaper than hydrogen produced using natural gas or coal combined with carbon capture and storage.

2.3. Battery and hydrogen storage in Germany

The German cumulative grid-scale battery installed capacity grew sharply from 2 MW in 2013 to 416 MW in 2019 (Jankowska et al., 2020). Accelerated deployment rates can be attributed to falling prices and the introduction of new compensation levels for primary control services. In 2020, innovative auctions were also introduced to promote projects combining fluctuating and non-fluctuating RES (BMJV, 2020). At the time of writing, three auction rounds had been conducted, and biannual rounds representing nearly 5 GW in total installed capacity were planned between 2022 and 2028 (BMWi, 2021a). Despite the auction mechanism being technology-neutral, it contributed mainly to the deployment of projects combining solar photovoltaic (PV) with battery storage.[39] However, beyond these mechanisms, current regulations sometime hinder the economic viability of battery storage (Ländner et al., 2019). Reforms in the German legal framework are thus required to address the issue of asset profitability (Jankowska et al., 2020).

Green hydrogen production and storage technologies are also expected to play an important role in the decarbonization of the German energy system. Despite these technologies being at an early stage of deployment, with few plants in operation, the 2020 national hydrogen strategy introduced ambitious production goals of increasing

[37] This cost is still five times greater than systems made in China (BloombergNEF, 2020a, p. 27).
[38] Based on current natural gas prices in China, Germany, and Scandinavia, for example.
[39] More information on the results of the German innovation auction is available here: https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Ausschreibungen/Innovation/BeendeteAusschreibungen/BeendeteAusschr_Innov_node.html

capacity to 5,000 MW_e by 2030, and an additional 5,000 MW_e by 2040 at the latest (BMWi, 2020a). In this strategy, hydrogen is presented as a promising low-carbon substitute to the fuels used in the carbon-heavy industry, transport, and building sectors (BMWi, 2020a). In Germany, hydrogen technologies could also contribute to solving the seasonal storage problem emerging from the mismatch between the power demand and RES supply (Jankowska et al., 2020). Although current low round-trip efficiency and high costs present major drawbacks, German industrial-scale supply of green hydrogen could soon become cost-competitive given adequate incentives. Policy support such as price premiums for renewable hydrogen generation and rabates and tax credits for electrolyser investments could make green hydrogen competitive with fossil-based hydrogen by the end of the decade (Glenk and Reichelstein, 2019). To reach the goals set by the German hydrogen strategy, the government recently set-up a task force on tendering sites for offshore green hydrogen production which could be introduced in 2022 (BMWi, 2021b).

This section has provided a comprehensive overview of key grid-scale ESS technologies. It also showed how recent developments in grid-scale battery storage and hydrogen production and storage offer promising solutions to the integration of variable RES into energy systems. Against this background, this study focuses on Li-batteries as the technology offers great versatility in terms of applications and recently garnered investor interest due to sharp price decreases. It also focuses on green hydrogen production and storage, as these technologies could offer a low-carbon solution to the issue of seasonal storage. Investigating what kind of support would be required to prompt investment in these technologies is important since additional policies are required to foster their large-scale deployment.

3. Methodology

3.1. Methodological approach and survey structure

The preferences of utility company representatives and institutional investors for clean energy investments can be investigated using stated- or revealed-preference methods. Choice experiments, a class of stated-preference methods, have their theoretical underpinnings in discrete choice and random utility theory (Lancaster, 1966; McFadden, 1980, 1974). The approach postulates that products or investments can be

decomposed into sets of attributes, and that their total utility corresponds to the sum of the part-worth utilities for the choice object's attributes. Preferences are elicited by requiring participants of experiments to choose between different investment concepts described by bundles of attributes that vary in terms of level. Since attribute levels are experimentally manipulated, the proposed investment concepts can be more diverse than those actually observed on markets (Holmes et al., 2017). This makes this approach particularly suited to investigating preferences for grid-scale batteries and especially green hydrogen investment, which is at an early stage of diffusion (Louviere et al., 2000; Rao, 2014). A lack of historical data makes the use of revealed-preference methods unsuitable.

In this study, an adaptive choice-based conjoint analysis (ACBC) was used to solicit investment decisions from institutional investors and utility company representatives. Several scholars have already used this method to investigate the preferences of investors for clean energy investment (Gamel et al., 2016; Melliger and Lilliestam, 2021; Petrovich et al., 2019). ACBC builds on two types of conjoint methods,[40] combining the advantages of using both self-explicated and choice tasks. Requiring respondents to first assess the desirability of specific investment features allows us to subsequently present concepts that are tailored to individual utilities, resulting in greater statistical efficiency (Huber and Zwerina, 1996). The method also recognizes the role non-compensatory strategies or heuristics may play in investment decisions (Johnson and Orme, 2007).

The survey was programmed using Sawtooth Software's module SSI Web and comprised three parts. First, we asked questions regarding prior clean energy investment experience, ESS investment barriers, and expected revenue streams. Second, we used ACBC questions to elicit respondents' stated preferences for clean energy investment (see Subsection 3.2 for more details). Third, the questionnaire concluded with a set of questions about socio-economic variables. The survey and ACBC design were pre-tested with experts to validate their adequacy and relevance between October and November 2020, prior to the data collection phase.

[40] Namely, adaptive conjoint analysis (ACA) and choice-based conjoint analysis (CBC). ACA first investigates the desirability of attributes and levels through self-explicated tasks. Then, investor preferences are clarified through rating partial profiles. In contrast, CBC investigates preferences by requiring respondents to evaluate competing concepts (Rao, 2014). CBC is widely used since choice tasks provide a more realistic decision setting than rating tasks. However, choice tasks tend to be less informative as they do not reveal the strength of individual preferences.

3.2. ACBC design

The ACBC was comprised of three subparts. First, the choice experiment was introduced, and respondents were informed that they would be presented with different equity investment opportunities and asked to make investment-related decisions. The introduction provided a comprehensive description of the experimental stimulus – namely, a hypothetical equity investment opportunity on the German energy market – and its characteristics (see Subsection 3.3 for details on the variable, attributes, and levels presented to respondents).

Second, the following instructions were shown to participants: "*Below, you will find different equity investment options. Please mark the options that could ("Yes") or could not ("No") be an investment for your company in real life. If your company would never consider a certain type of equity investment […], please also reject the related investment opportunities in this survey. Risk-return profiles may not necessarily be in line with market expectations as they should reflect a broad range of investment preferences*." Randomized investment concepts that varied in terms of expected returns and attribute levels were presented in groups of four. Participants were asked whether each concept could be an investment possibility for their company (see Figure 1 for an example of a screening task and Subsection 3.3 for additional information about concept design). If participants systematically avoided certain characteristics, lists of attribute levels were presented so that they could indicate if they deemed any features to be unacceptable. In total, 32 screening concepts were presented to clarify potential screening rules.

Gross IRR	5%	9%	2%	11%
Technology	Solar PV	Solar PV + hydrogen electrolyser and storage	Solar PV + battery storage	Solar PV + battery storage
Fixed compensation	100%	60%	60%	60%
Partner	International company	German state	Local company	International company
Business model	Own development, construction and operation	Outsourced development and construction, own operation	Outsourced development, construction and operation	Own development, construction and operation
	◉ Yes ◉ No	○ Yes ○ No	◉ Yes ◉ No	○ Yes ○ No

Figure 1: Example of ACBC screening task.

Third, a series of choice tasks were presented, and respondents were asked to select their preferred option among three tailored investment concepts. Attribute levels that

were equal across all concepts were highlighted to facilitate decision-making. Tournament rounds were displayed until the preferred concept was derived. For all screening and choice tasks, respondents could look up the definitions of any attributes and attribute levels by scrolling their pointer over each feature to avoid confusion or misinterpretation during the choice experiment.

3.3. Selection of the return variable, attributes, and attribute levels

A return variable, attributes, and attribute levels were selected based on insights obtained from a pre-study, which included a review of relevant literature, five semi-structured interviews conducted between September and November 2020 with high-level institutional investors and utility company representatives, expert consultations, and prior research conducted internally. Correspondingly, a return variable and four attributes were identified as key factors for clean energy investment decisions, as illustrated in Table 2. Attribute levels were selected to provide choice options that reflect market developments and trends.

Table 2: Variable and attributes manipulated in the ACBC.

Variable and Attributes	Description	Continuous price variable and attribute levels
Gross IRR	Forecast annual return on investment before fees and taxes.	- Continuous price variable varies between 1% and 13%
Technology	Type of clean energy technology.	- Solar PV - Solar PV + battery storage - Solar PV + hydrogen electrolyser and storage
Fixed compensation	Share of total revenue with fixed compensation.	- 100% - 60% - 20%
Partner	Type of counterpart providing the fixed compensation.	- German state – fixed compensation provided via a state incentive scheme - International company – fixed compensation provided via a bilateral agreement - Local company – fixed compensation provided via a bilateral agreement
Business model	Parts of the project value chain process that are sub-contracted.	- Outsourced development, construction, and operation - Outsourced development and construction, own operation - Own development, construction, and operation

The gross internal rate of return ("*Gross IRR*") represents the expected annual yield an investment option could provide before fees and taxes. Since ESS returns often stem

from a mixture of regulated and market-driven contracts (IEA, 2020d), the "*gross IRR*" can incorporate a combination of fixed and variable revenue streams, as specified by the "*fixed compensation*" and "*partner*" attributes. Stacking revenue streams[41] is often found to be desirable to increase asset value. "*Gross IRR*" was operationalized as a continuous price variable. Prices displayed ranged between 1% and 13%. This approach permitted the collection of high precision data by showing respondents a larger number of unique prices (Sawtooth Software, 2021a).

The "*technology*" attribute included three alternatives – namely, solar PV, solar PV combined with battery storage, and solar PV combined with electrolyser and storage. More specifically, Li-battery and PEM-electrolyser technologies were used in the experiment. These combinations were designed to reflect recent technological trends. Solar PV has become one of the cheapest energy sources (IEA, 2020h). In 2019, nearly half of all grid-scale battery capacity installed globally was co-located with power plants, mostly solar PV (IEA, 2020d).[42] Most successful bids in the German innovation auction also combined solar PV and batteries. Further, combining low-cost solar PV with hydrogen technologies could represent a promising configuration (Mallapragada et al., 2020). Similar projects have been announced in Europe (BMWi, 2020b; Sánchez Molina, 2020). Defining such attribute levels permits the estimation of the extent to which professional investors differentiate between these technologies.

The "*fixed compensation*" attribute specifies the share of total revenues fixed over the project lifetime. The remaining part is exposed to electricity price risk. The attribute included levels of 100%, 60%, and 20% of fixed compensation. In Germany, fixed revenues can mainly be obtained through contractual agreements with counterparties, as specified by the "*partner*" attribute. Variable revenues are obtained through trades on merchant markets such as the spot market for delivery within a week, or the forward market for long-term delivery. These attribute levels allow an evaluation of whether and to what extent electricity price risk affects investment decisions.

The "*partner*" attribute indicates the type of partner that provides the fixed compensation (either by a physical offtake or a financial hedge) – namely, the German state, an international company, or a local company. In Germany, the state has historically incentivized renewable energy investment typically through feed-in-tariff

[41] Understood as the diversification and aggregation of revenue streams for a given asset through value creation and the provision of several services.
[42] Notably, 300 MW was co-located with solar PV plants, and 115 MW with wind parks.

incentives, which has resulted in substantial deployment. Following considerable technology cost degression, new mechanisms were introduced. A fixed market premium with a ceiling price of 7.5 cents/kWh is granted to bidders who are successful in innovation auctions (BMJV, 2020).[43] Regulated revenues such as capacity or commodity charges can also be obtained from transmission system operators for the provision of ancillary services (Jankowska et al., 2020). Further, fixed compensation can be ensured via bilateral power purchase agreements (PPA), similar to feed-in-tariffs but arranged with various private counterparts, including internationally or locally operating companies. This attribute permits clarification of whether investors have preferences for specific partners providing them with fixed compensations.

Finally, the "*business model*" attribute specifies the parts of the project value chain process that are sub-contracted. Development, construction, and operation can be fully outsourced, partly outsourced, or fully owned. This attribute design provides important insights into the willingness of an investor to take on different project-related risks.

3.4. Data collection and sample

This study targeted institutional investors[44] and representatives from utility companies in high-level positions who are interested in clean energy investment. The focus was on companies of all sizes active in Europe, in particular Germany. Relevant companies were identified using three databases,[45] conference attendance lists, and web searches. High-level decision-makers were identified through company websites or a professional social media platform by using keywords like "managing director" or "investment manager". Contact information such as names, job positions, and e-mail addresses were acquired through public websites or by using the University's network. As a result, a total of 536 invitations were successfully sent to utility representatives (213) and institutional investors (323) via email and a social media platform. Most

[43] The average strike price of the first three rounds of the German innovation auction ranged between 4.29 cents/kWh and 4.55 cents/kWh (Bundesnetzagentur, 2021). These values are considerably lower than the ceiling price which could start decreasing annually from 2022 onwards (see *Innovationsausschreibungsverordnung* (InnAusV), §10 subsection (2) for further details).

[44] More specifically, representatives from pension funds and insurance companies were targeted as they play an important role in financing clean energy infrastructure. Manager of infrastructure funds active in the clean energy sector were also included as their primary sources of capital are often pension funds and insurance companies (Hamilton and Zindler, 2016). In addition, representatives from the direct infrastructure investment division of banks active in the power sector were also considered.

[45] The databases had been developed internally by systematically researching institutional investors and utility companies active in the European clean energy market. The databases include companies of all sizes.

potential respondents were contacted twice through an initial message and a reminder sent between November 2020 and January 2021. Respondents who were reached via direct messaging on a social media platform were contacted only once, since the latter prevent sending reminders unless the first message is accepted by the user. A brief description of the study, the survey link, and information about data usage and confidentiality were provided upon contact. Access to the study results was also offered to respondents.

Table 3 provides information on the sample and response rates. A total of 97 respondents accessed the survey. Incomplete responses (46), respondents who did not correspond to the target group such as project developers (4), and double entries (5) were excluded. The final sample comprises 42 survey respondents who conducted a total of 1,605 investment-related decisions, equalling to a response rate of 7.8%. Although this sample size is in line with prior studies undertaking research in similar contexts (Botta, 2019; Chassot et al., 2014; Loock, 2012; Melliger and Lilliestam, 2021), it is not comparable to studies undertaken with non-professional RES investors. This is likely due to our choice of focusing on specific investor groups, the relatively early stage of ESS investment diffusion, our specific geographical focus, and the considerable challenge associated with surveying high-level decision-makers who are often time constrained. Finally, five respondents completed the questionnaire partially but provided sufficient information for their insights to be included in the analysis.

Table 3: Survey sample and response rates.

	No. of responses	**Response rate**
Survey invitations	**536**	
Utility companies	213	
Institutional investors	323	
Survey retrieved	**97**	**18.1%**
Utility companies	50	23.5%
Institutional investors	47	14.6%
Surveys completed	**42**	**7.8%**
Utility companies	20	9.4%
Institutional investors	22	6.8%

Survey respondents are predominantly males, on average in their mid-forties. The experience of both investor groups with clean energy investment is comparable, with the majority having between 5 and 15 years of experience. Nearly two third of utility respondents work for local or regional companies, whereas half of institutional investor

respondents work for mid-sized and large investment funds. Most respondents also reported being based in Germany (38%) or Switzerland (49%). Further information on the sample socio-demographic data can be found in Table A.1 in the appendix.

4. Results and discussion

In this section, descriptive results about previous clean energy investment experience, investment barriers, and expected revenue streams are first presented. Results of the choice experiment conducted to investigate preferences for clean energy investments, attribute importances, and willingness to accept investment features are then examined. Since the choice experiment focused on the German market and as most respondents reported being based in Europe, the insights presented in this section are likely to reflect these contexts.

4.1. Descriptive results

4.1.1. Prior clean energy investment experience

Similar shares of utility company representatives (hereafter, utility respondents) and institutional investor representatives (hereafter, institutional investors) have previously invested in mature clean energy technologies, but relatively more utility respondents reported having invested in battery storage and green hydrogen production and storage (see Figure 2). Survey results show that most respondents have previously invested in technologies like solar PV and onshore wind energy. Such a finding substantiates the global trend to the deployment of these technologies (IRENA, 2020a). Both investor groups also reported to having had similar investment experience with pumped hydro. However, more than twice as many utility respondents (65%) stated that they had invested in battery storage compared to institutional investors (25%).

This difference may be explained by their contrasting business strategies. Consistent with prior research (Helms, 2016; IRENA, 2020b), utility respondents tend to have been engaged in many project phases, in particular development (75%) and operation (80%), whereas institutional investors tend to mostly subcontract greenfield activities[46] to focus

[46] Greenfield activities refer to the development and construction of new assets, in contrast to brownfield projects which are understood here as operational assets which may require alterations (IRENA, 2020a).

on the ownership of operational clean energy assets (80%) (see Figure A.1 in the appendix). Since utility companies are more involved in operating clean energy projects and trading electricity, activities may become more challenging with a growing share of variable RES in their portfolios. This could incentivize them to invest more than institutional investors in technologies that confer more flexibility, such as battery storage, with a view to optimizing their operations and hedging them against wholesale market price fluctuations. Further, despite institutional investors playing an increasing role in acquiring and refinancing clean energy assets (IEA, 2020d), the potential of ESS institutional investment is underutilized. Research shows that viable ESS business cases may entail stacking revenue streams such as returns obtained from price arbitrage that would induce market risk exposure (Lombardi and Schwabe, 2017; Martins and Miles, 2021). This may represent a barrier to institutional investment, as such investors tend to prefer reliable cash flows (IEA, 2020d).

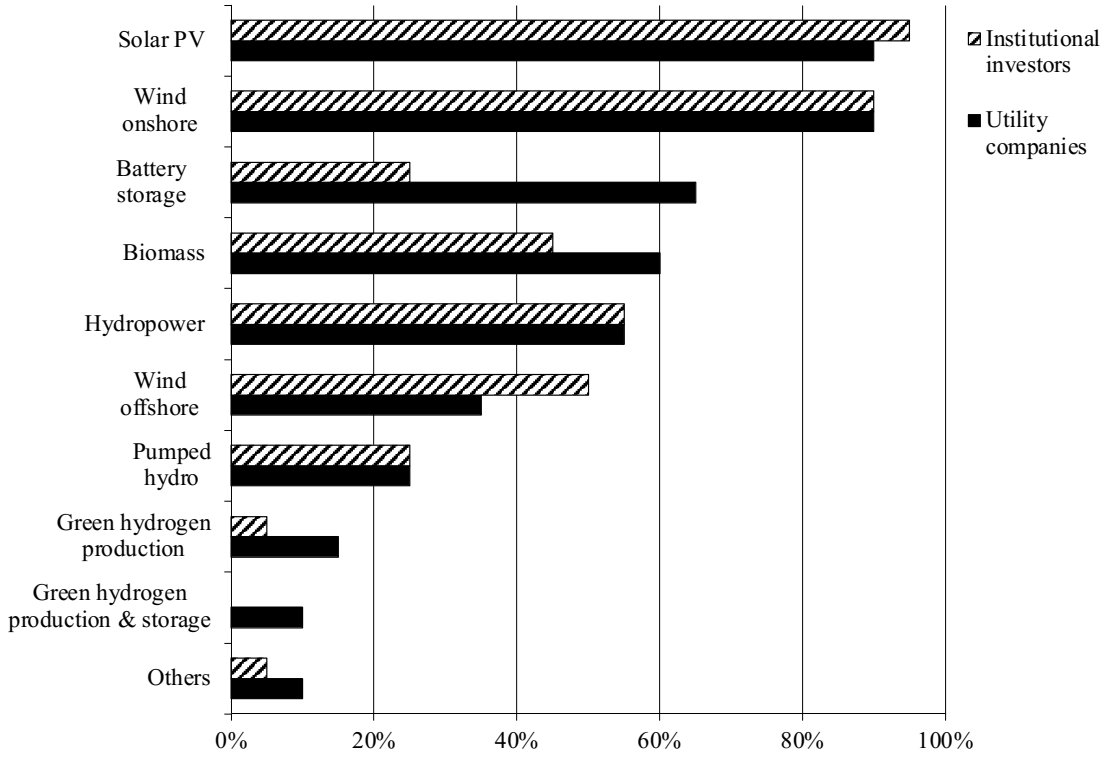


Figure 2: Share of respondents with previous investment experience according to type of technology (multiple answers possible, N=20 / N=20).

Although institutional investors exhibit a strong preference for operational assets, the survey results also highlight early-stage investment experience. Interestingly, a quarter of institutional respondents reported prior involvement in clean energy project development. This finding is surprising as it differs from existing studies reporting

considerably lower shares of institutional investors involved in project development (Salm, 2018). This trend could be driven by the pressure to take higher project risk to maintain absolute return levels, a pressure resulting partly from the low interest rate environment and increased competition for clean energy investment (IRENA, 2020b). It could also be driven by the gains in maturity and price fall observed for certain technologies like solar PV (Egli, 2020). These factors were highlighted during our pre-study interviews. However, this development may not apply to clean energy assets that are associated with high technological risk. Finally, the COVID-19 pandemic may have contributed to exacerbate the competition for clean energy investments. Indeed, almost a third of institutional investors reported a surge in competition as an outcome of the crisis (see Figure A.2 in the appendix). Nevertheless, despite an equal share of institutional investors and utility respondents (35%) reporting delays in development and construction, the majority of respondents foresaw no major long-term impact of the pandemic.

4.1.2. Energy storage barriers and expected revenue streams

Policies aimed at ensuring attractive yields could help overcome barriers to ESS investment. When asked to rank the two most important reasons for investing in clean energy technologies, both utility respondents (50%) and institutional investors (41%) pointed first towards the necessity of favourable return profiles (see Table A.2 in appendix). Portfolio diversification was ranked second by utility respondents (30%), whereas capturing growth opportunities was second for institutional investors (23%). These findings are in line with previous studies that suggest that both groups prioritize financial over non-financial motives (Blondiau and Reuter, 2019). When asked to rank the two most important barriers to ESS investment, a lack of available business cases was ranked first by institutional investors (41%) and utility respondents (25%). An equivalent share of utility respondents (25%) also ranked comparably low returns as the first impediment to investment. Lower returns were ranked as the second most important barrier for utility respondents (25%), whereas institutional investors (27%) reported a lack of governmental support as the second most important hindrance. These findings support research which shows that uncertainty and risk, low returns, and a lack of policy support are impediments to clean energy investment (Biresselioglu et al., 2020; Ländner et al., 2019). They also underline the important role that sound policies could play in rendering ESS returns sufficiently attractive to investors.

Utility respondents have a more consolidated view than institutional investors regarding future battery storage revenue streams (see Table 4). Peak shaving is foreseen as the most important revenue source for utility respondents (55%), followed by frequency reserve (35%). Research shows that combining peak shaving with operations like self-consumption or spot market trading could generate attractive returns (Lombardi and Schwabe, 2017). In contrast, and somewhat surprisingly, institutional investors view frequency reserve (32%) as the most important revenue stream, followed by intraday energy arbitrage (23%). This could be explained by the fact that in some countries where energy systems are broadly liberalized like Germany where 40% of our institutional investor respondents are based, revenues derived from grid control services are regulated by system operators through an auction mechanism. Successful bidders are compensated through capacity charges, a source of revenue that is more likely to be reliable than trading power on wholesale markets. This lower level of exposure to electricity price risk could explain why institutional investors in our sample foresee frequency reserve as a more promising source of revenue than price arbitrage. This may however not hold true in all markets. Scholars also find that price arbitrage could represent an attractive business case when electricity price differences between peak and off-peak periods are large (Lin and Wu, 2017). However, relying solely on wholesale market revenues may be challenging for asset finance, as commercial debt may be limited for projects with variable income streams in certain jurisdictions (IEA, 2020d). This underlines the important role stacking revenues could play in rendering battery storage investments viable, notably through combining fixed and variable revenue streams.

Utility respondents also have a more uniform outlook about future green hydrogen revenues than institutional investors. Seasonal storage is foreseen as the most or second most important source of revenue for utility respondents (55% and 30%, respectively). This finding shows that addressing the seasonal mismatch between power generation and demand is regarded as a promising application for the technology, underlining its potential key role in future energy systems. In contrast, 23% of institutional investors highlighted bilateral offtake agreements with industry partners as the main source of revenue that is foreseen. The provision of an uninterruptable power supply and peak shaving were also both ranked second (18%) by respondents. Finally, studies show that stacking cross-sectoral revenues may also help render green hydrogen investments viable (Farag et al., 2020; Mukherjee et al., 2017). Similarly, utility respondents (95%)

and institutional investors (91%) mostly foresee future ESS business cases as including multiple revenue streams.

Table 4: Most important revenue streams for battery storage and green hydrogen production and storage going forward (one answer per factor).

		Utility companies (N=20)		Institutional investors (N=22)	
		1st Rank	**2nd Rank**	**1st Rank**	**2nd Rank**
Two most important revenue streams for battery storage	Energy arbitrage (intraday trading)	20.0%	20.0%	9.1%	22.7%
	Energy arbitrage (day-ahead trading)	5.0%	0.0%	4.5%	9.1%
	Frequency reserve (primary control reserve)	10.0%	35.0%	31.8%	4.5%
	Frequency reserve (other)	0.0%	0.0%	0.0%	4.5%
	Black-start	0.0%	0.0%	0.0%	4.5%
	Uninterruptable power supply	0.0%	5.0%	13.6%	9.1%
	Peak shaving	55.0%	25.0%	13.6%	18.2%
	Seasonal storage	0.0%	0.0%	0.0%	0.0%
	Capacity market (if available)	5.0%	5.0%	18.2%	9.1%
	PPA with industry partner	0.0%	5.0%	9.1%	18.2%
	Co-located with mobility fuelling station	0.0%	5.0%	0.0%	0.0%
	Others	5.0%	0.0%	0.0%	0.0%
Two most important revenue streams for green hydrogen production and/or storage	Energy arbitrage – intraday trading	5.0%	5.0%	4.5%	9.1%
	Energy arbitrage – day-ahead trading	5.0%	5.0%	4.5%	4.5%
	Frequency reserve – primary control reserve	0.0%	10.0%	9.1%	0.0%
	Frequency reserve – other	0.0%	0.0%	4.5%	4.5%
	Black-start	0.0%	0.0%	0.0%	0.0%
	Uninterruptable power supply	10.0%	0.0%	13.6%	18.2%
	Peak shaving	0.0%	15.0%	0.0%	18.2%
	Seasonal storage	55.0%	30.0%	18.2%	9.1%
	Capacity market (if available)	0.0%	10.0%	13.6%	4.5%
	PPA with industry partner	5.0%	5.0%	22.7%	13.6%
	Co-located with mobility fuelling station	20.0%	15.0%	0.0%	4.5%
	Others	0.0%	5.0%	9.1%	13.6%

4.2. Preferences for investment features

Attribute level utilities, or part-worths, are estimated by specifying a Hierarchical Bayes (HB) model using the Sawtooth Software. The model is derived by applying Bayesian methods and includes two sub-models for describing individual preferences and sample heterogeneity. Participants are assumed to repeatedly select their preferred investment concepts based on aggregated part-worths. Hence, a within-unit multinomial

logistic model specifies the choice probability at the individual level. In the across-unit model, participants' decisions follow a single multivariate normal distribution described by a mean vector and variance-covariance matrix (Allenby et al., 2005; Orme and Howell, 2009; Rao, 2014). This approach allows us to address potential lack of information at the individual level by accounting for the choices of other participants and is particularly suitable for smaller datasets.

Average root likelihood (RLH) parameters are used to provide an indication of the quality of the HB model through quantifying the match between utility estimates and actual participant choices. RLH represents the geometric mean of all predicted probabilities. It is derived using the n^{th} root of likelihood, n being the number of choice task alternatives. The highest fit is indicated by RLH=1. Since the ACBC design included three concept per choice task, the null likelihood is RLH=0.33 (Sawtooth Software, 2021b). High RLH values were identified for the given datasets, revealing good model quality (institutional investors RLH=0.78; utility respondents RLH=0.74). Table 5 presents zero-centred utilities, the lower and upper 95% confidence intervals (CI), standard deviations (SD), and unacceptable levels. Part-worth estimates were zero-centred to facilitate comparison within attributes.

Results show that the expected return is the most influential attribute for all investors. Zero-centred utility estimates also suggest that both investor groups prefer to invest in relatively mature *technologies* like solar PV, followed closely by solar PV combined with battery storage. Despite reporting having less experience with battery storage and green hydrogen production and storage investment, institutional investors appear to be less reluctant than utility respondents to invest in new technologies as the spread between their zero-centred utilities is smaller. This claim is also underlined by the relatively high share of utility respondents (20%) who stated that solar PV combined with electrolyser and storage would never be an investment option for their company. In contrast, none of the institutional investors stated that any of the technologies were fully unacceptable.

Table 5: Zero-centred utilities, lower and upper 95% confidence intervals (HB model with utilities normally distributed), standard deviations and unacceptable levels.

		HB model utility companies (N=20)				HB model institutional investors (N=22)			
Attribute	**Attribute levels**	**Zero-centred utilities**	**Lower and upper 95% confidence intervals**	**Standard deviations**	**Unacceptable level in %**	**Zero-centred utilities**	**Lower and upper 95% confidence intervals**	**Standard deviations**	**Unacceptable level in %**
Gross IRR	1%	-89.82	[-110.43: -69.21]	47.02		-99.79	[-122.75: -76.83]	54.94	
	13%	89.82	[69.21: 110.43]	47.02		99.79	[76.83: 122.75]	54.94	
Technology	Solar PV	15.14	[5.00: 25.28]	23.13	0.00	9.07	[1.34: 16.79]	18.48	0.00
	Solar PV + battery storage	13.76	[3.70: 23.82]	22.96	0.00	5.94	[2.17: 9.70]	9.01	0.00
	Solar PV + hydrogen electrolyser and storage	-28.90	[-46.26: -11.54]	39.62	20.00	-15.00	[-24.80: -5.20]	23.45	0.00
Fixed compensation	100%	38.75	[30.68: 46.83]	18.42	0.00	47.57	[38.72: 56.43]	21.19	0.00
	60%	5.38	[-0.49: 11.25]	13.40	0.00	19.05	[10.93: 27.17]	19.44	4.55
	20%	-44.14	[-54.32: -33.95]	23.25	15.00	-66.62	[-81.04: -52.21]	34.50	27.27
Partner	German state	16.32	[5.51: 27.14]	24.68	0.00	2.26	[-12.18: 16.71]	34.56	9.09
	International company	-23.63	[-37.18: -10.08]	30.91	5.00	2.26	[-6.99: 11.50]	22.13	4.55
	Local company	7.31	[-7.31: 21.93]	33.35	0.00	-4.52	[-15.47: 6.43]	26.20	0.00
Business model	Outsourced development, construction, & operation	-17.29	[-40.72: 6.14]	53.47	15.00	23.48	[10.54: 36.43]	30.98	0.00
	Outsourced development & construction, own operation	-2.09	[-16.10: 11.92]	31.97	5.00	15.32	[6.48: 24.17]	21.17	9.09
	Own development, construction & operation	19.38	[-12.78: 51.54]	73.37	5.00	-38.80	[-55.29: -22.32]	39.46	22.73

Interestingly, both investor groups also prefer higher shares of *fixed compensation*. This attribute appears to play a central role in investment decisions, as both groups stated that a 20% fixed compensation would be unacceptable for their companies (27% institutional investors, 15% utility respondents). Fixed compensation may play a greater role for institutional investors, with one respondent claiming that even 60% fixed revenue would not be sufficiently attractive. Regarding the type of *partner* providing the fixed compensation, utility respondents have a relatively stronger preference for the German state. In contrast, institutional investors would generally be more open to concluding agreements with different types of partners, as the spread between their zero-centred utilities is smaller.

In terms of the *business model*, utility respondents prefer developing, constructing, and operating projects. This proposition is also supported by the share of utility respondents (15%) who reported that outsourcing these activities would be unacceptable for their company. In contrast, institutional investors are more inclined to own operational assets whilst outsourcing other activities. This is also underlined by the share of institutional investors (23%) who indicated that undertaking such activities would not be an option. These findings deviate from those in previous studies which show that both investor groups prefer to own assets and outsource other activities (Salm, 2018). As explained in Subsection 4.1.1, increasing competition for clean energy investment may prompt institutional investors to get involved at an earlier stage to secure opportunities. Further, these results corroborate the findings about technological preferences described in this subsection. Since utility respondents are more likely to engage in development, construction, and operation activities, they might be more reluctant to invest in less mature technologies.

4.3. Average continuous price variable and attribute importances

Average importance scores are derived using the Sawtooth Software to reflect the relative weight the continuous price variable and attributes have in investment choices. Table 6 presents average importance scores and standard deviations. Results show that while utility respondents and institutional investors both indicated that the *gross IRR* is the most impactful factor in their investment decisions (35.93% and 42.83%, respectively), the relative importance of all other attributes differs between the two groups. Utility respondents consider *business models* as the second most important attribute (21.52%), whereas institutional investors are more concerned with financial

attributes like *fixed compensation* (23.07%). Results from a Mann-Whitney *U* test underline the significant distinction in average importances between the two groups for the fixed compensation attribute ($p<.05$), confirming institutional investors' aversion to electricity price risk exposure. Next, utility respondents rank *fixed compensation* (16.95%), *technology* (13.59%), and *partner* (12.02%) in declining order as influences on their clean energy investment decisions. In contrast, institutional investors rank *business model* (15.26%), *partner* (10.58%) and *technology* (8.26%) as least important. Finally, there is also a significant difference between the two groups in terms of average importances for the technology attribute ($p<.05$), highlighting utility respondents' reluctance to take technology-related risks.

Table 6: Average importances and standard deviations of the continuous price variable and attributes.

	Utility companies (N=20)		**Institutional investors (N=22)**	
Attribute and variable	**Average importances**	**Standard deviations**	**Average importances**	**Standard deviations**
Gross IRR	35.93	18.81	42.83	15.18
Technology	13.59[a]	9.12	8.26[a]	4.98
Fixed compensation	16.95[a]	7.61	23.07[a]	10.64
Partner	12.02	10.66	10.58	8.12
Business model	21.52	15.18	15.26	11.42

[a] Average importances differ significantly between investor groups ($p<.05$).

4.4. Willingness to accept

Subsection 4.2 clarified preferences in relation to investment features. Here, aggregated willingness to accept (WTA) values were estimated based on Lüthi and Wüstenhagen (2012) to quantify the additional compensation investors would require to accept an investment with less preferred features compared to one with the most preferred ones. This approach was also used by other scholars to estimate investors' marginal WTA of certain policy risks and clean energy investment features (Botta, 2019; Salm and Wüstenhagen, 2018). Figure 3 illustrates the WTA results. A WTA = 0 percentage point corresponds to the most preferred investment feature. Positive WTA values represent the average premium respondents would require to accept an investment with a less preferred feature compared to one with the most preferred one.

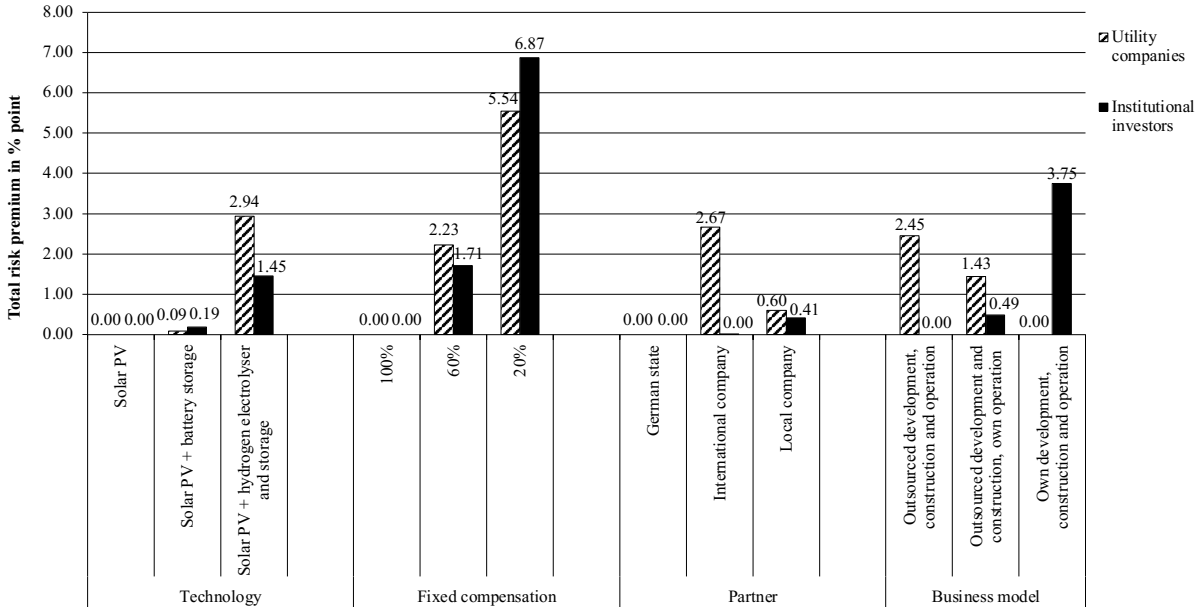


Figure 3: Willingness to accept (N=20 / N=22).

The WTA analysis indicates that combining solar PV with battery storage would result in relatively small premium requirements compared to combining it with hydrogen electrolyser and storage. Utility respondents would require an average premium nearly twice as large as that of institutional investors to accept the latter technological combination (2.94 percentage points and 1.45 percentage points, respectively). These findings underline the reluctance of utility respondents to take *technology*-related risks. *Fixed compensation* is the attribute associated with the highest premium. Utility respondents would require an average compensation of 5.54 percentage points to accept to move from an investment with 100% fixed compensation to one where only 20% of the revenues are fixed, and institutional investors would require 6.87 percentage points. These results further underline the importance for investors to secure predictable cash flows.

Further, WTA results confirm that the German state is the most preferred *partner* for both groups. Yet, as mentioned in Subsection 4.2, institutional investors appear to hardly differentiate between partners as they require only a marginal premium to change counterparts. In contrast, utility respondents would require a higher average premium (2.67 percentage points) to conclude an agreement with an international company. This reluctance to partner with international companies may be explained by the fact that most utility respondents reported working for local or regional companies. They may thus be favourably inclined to work with other local actors.

Finally, WTA results substantiate the finding that institutional investors are overall very hesitant to take over development risk, while utility respondents would not accept anybody else developing their projects. Both investor groups would ask for significant premiums to overcome their reluctance (3.75 percentage points and 2.45 percentage points, respectively). As discussed in Subsection 4.2, these findings may also explain why utility respondents appear to be less willing to explore new technological ventures: namely, that the latter do not have the resources or know-how to develop such projects. Since institutional investors prefer turnkey opportunities where all the development work is finalised, they appear to be more open to risk-taking. Prior research also confirms that utility companies are relatively slower at adopting innovations (Curtin et al., 2019; Helms et al., 2020).

5. Conclusion and policy implications

Considerable investment in energy storage is needed to integrate the growing share of variable renewable energy sources into energy systems and meet climate-neutrality goals. Policies may play an important role in rendering investments sufficiently attractive to private investors, in particular regarding battery storage and less mature technologies such as green hydrogen production and storage. However, there is a lack of empirical evidence concerning what kind of support would be required by different types of investors to unlock investment. To address this issue, this study applied a choice experiment to investigate and quantify the willingness to invest of 42 high-level institutional investors and representatives from utility companies who made 1,605 investment-related decisions in the German context.

Unsurprisingly, results show that return is the most relevant investment characteristic. Energy market risk is also found to be a central element in energy storage investment decisions, as both institutional investors and utility respondents would require considerable premiums to move from an investment with 100% fixed compensation to one with 20% (6.87 percentage points and 5.54 percentage points, respectively). This claim is also supported by the fact that both investor groups stated that 20% fixed compensation would be unacceptable for their companies (27% institutional investors, 15% utility respondents). The importance of securing reliable cash flows appears even more decisive for institutional investors, as they ranked this factor second most important in investment decisions after the expected return. Utility respondents tend to prefer to obtain fixed compensation from the German state, whereas

institutional investors hardly differentiate between agreements with counterparts such as the German state, an international or a local company. Nevertheless, institutional investors identify a lack of governmental support (27%) as the second most important barrier to energy storage investment, after a lack of available business cases (41%). As a result, they tend to lend greater importance to applications which are likely to confer more reliable cash flows (primary control services and bilateral agreements with industry partners). Finally, most investors regard stacking revenue streams as key to making energy storage business cases viable. However, this may imply combining both fixed and market-based revenues.

Despite institutional investors disclosing some development experience, results show that they tend to be hesitant to take on greenfield activities, whereas utility respondents would not accept anybody else developing their projects. Diverging from these preferences would result in significant premium requirements (2.45 percentage points and 3.75 percentage points, respectively). These findings are also underlined by the fact that 23% of institutional investors deem developing their own project unacceptable, whereas 15% of utility respondents would not accept fully outsourcing greenfield activities. Since utility respondents tend to favour early-stage engagement, they may be more hesitant than institutional investors to explore new technological ventures if resources and know-how are limited. While both investor groups reported similar risk-return preferences for technologies such as solar photovoltaic combined with battery storage, utility respondents would require an average premium nearly twice as large as that of institutional investors to combine solar photovoltaic with green hydrogen production and storage. This apparent reluctance to take on technological risks is also underlined by the fact that 20% of utility respondents revealed they would never invest in such assets.

The insights drawn from this study underline the important role policies could play in mitigating energy market risk for investors. Since both investor groups revealed a high aversion towards non-regulated revenues, finding ways to hedge investors – at least partly – against exposure to electricity price risk may significantly reduce the financing cost of energy storage assets. This could be achieved through policy schemes such as fixed price premiums or corporate PPAs – although, the latter are perceived as being somewhat riskier than state-guaranteed policies, especially by utility companies. This could be interpreted as a signal for policy makers that, despite the abundance of corporate pledges to commit to climate change mitigation, investors perceive the ability of government in de-risking clean energy projects to be unmatched. Looking back, the

introduction of regulated revenues via frequency control reserve and innovative auction schemes has proved to play an important role in accelerating the deployment of battery storage in Germany. However, current auction volumes are still too small to trigger the levels of investment needed to support Germany's increasingly ambitious decarbonization goals (Battista, 2021). Since investors appear to see battery storage as more mature than green hydrogen technologies, scaling up auction volumes – similarly to other mature clean energy technologies like solar PV and wind – may provide a way to hedge investors against exposure to electricity price risk and reduce premium requirements.

Further, utility companies and institutional investors have complementary profiles when it comes to taking development and construction risk. While utility companies prefer to invest in greenfield projects, institutional investors would rather outsource such activities. Policy makers interested in increasing storage capacities could find ways to facilitate co-investment structures, thereby tapping into these complementarities. In such ventures, utility companies could be incentivized to lead greenfield activities and take early-stage technology risk, whereas institutional investors could acquire shares at a later stage of project development and provide financial premiums in exchange for taking lower levels of risk. The flexibility of institutional investors with regards to investing across different technologies make them well-suited parties for such consortia. However, sufficient levels of private investment may only be served when the needs of both investor groups are adequately addressed. Finally, as overcoming the reluctance of investors to invest in green hydrogen would require considerable premiums compared to battery storage, policy makers may wish to reflect carefully upon the role of this technology in the decarbonization of energy systems. Channelling support for green hydrogen towards applications where battery storage has limitations – e.g., long-term seasonal storage which is foreseen as a promising application by utility companies – would appear to be the most efficient way to allocate public resources.

This study has limitations which pave the way for further research. First, it investigates risk-return preferences of investors using a stated-preference method. While this approach is well suited to analyse forward-looking situations when historical data are lacking, not all respondents will act immediately upon their stated preferences. This may leave a gap between intentional versus actual investment decisions. Once sufficient market data become available, future research could elaborate on the actual investment behaviour and cross-investor differences based on revealed-preference methods. It could also seek at understanding differences across various types of institutional investors, or

other private investors such as project developers. Moreover, this study highlighted the important role fixed compensation could play in enabling energy storage deployment. Further research could also investigate what types of policy incentives are preferred by different investors, and what levels of remuneration are required. Finally, this study focuses on technological combinations which include solar photovoltaic – a mature and widely adopted energy source. Upcoming research could also explore other technological combinations, whether these include combining energy storage with wind energy, or hybrid power plants that combine solar and wind energy.

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Appendix. Additional results

Table A.1: Sample socio-demographic data.

Variable (number of responses utility companies / institutional investors)	Value	Utility companies	Institutional investors
Gender (N=17 / N=20)	Female	6%	15%
	Male	94%	85%
Age (N=17 / N=20)	Average	43	44
General work experience (N=17 / N=20)	Less than 5 years	6%	0%
	5 to 10 years	24%	10%
	10 to 15 years	18%	20%
	15 to 20 years	18%	25%
	20 to 25 years	18%	30%
	More than 25 years	18%	15%
Renewable energy and energy storage investment experience (N=17 / N=20)	Less than 5 years	24%	20%
	5 to 10 years	29%	40%
	10 to 15 years	29%	15%
	15 to 20 years	12%	15%
	20 to 25 years	0%	5%
	More than 25 years	0%	0%
	No investment experience in markets	6%	5%
Industry specification (N=20 / N=22)	Investment fund	0%	50%
	Pension fund	0%	14%
	Investment bank	0%	14%
	Insurance company	0%	14%
	Local/regional utility company	65%	0%
	Multinational utility company	35%	0%
	Others	0%	9%
Company size (N=17 / N=20)	1-9	0%	5%
	10-99	12%	35%
	100-499	29%	15%
	More than 500	59%	45%
Company nationality (N=17 / N=20)	Germany	35%	40%
	Switzerland	59%	40%
	United Kingdom	0%	15%
	Others	6%	5%

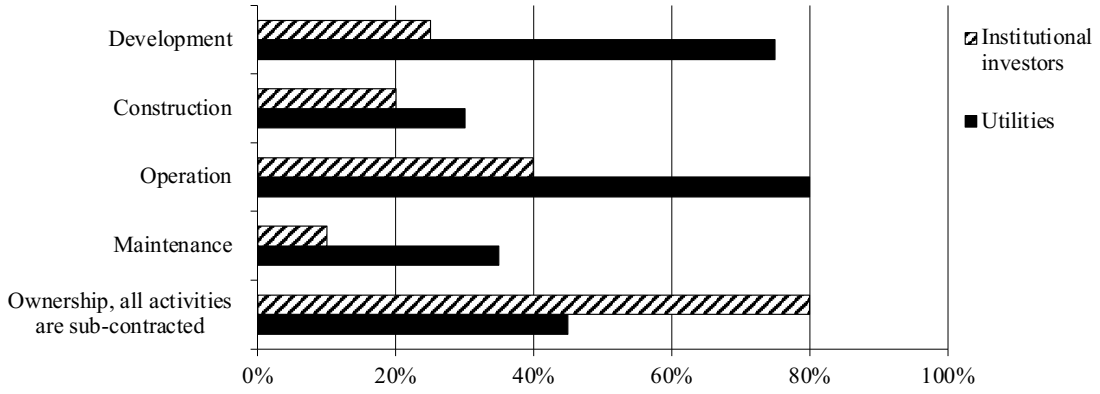


Figure A.1: Business models for renewable energy and / or energy storage equity investments (multiple answers possible, N=20 / N=20).

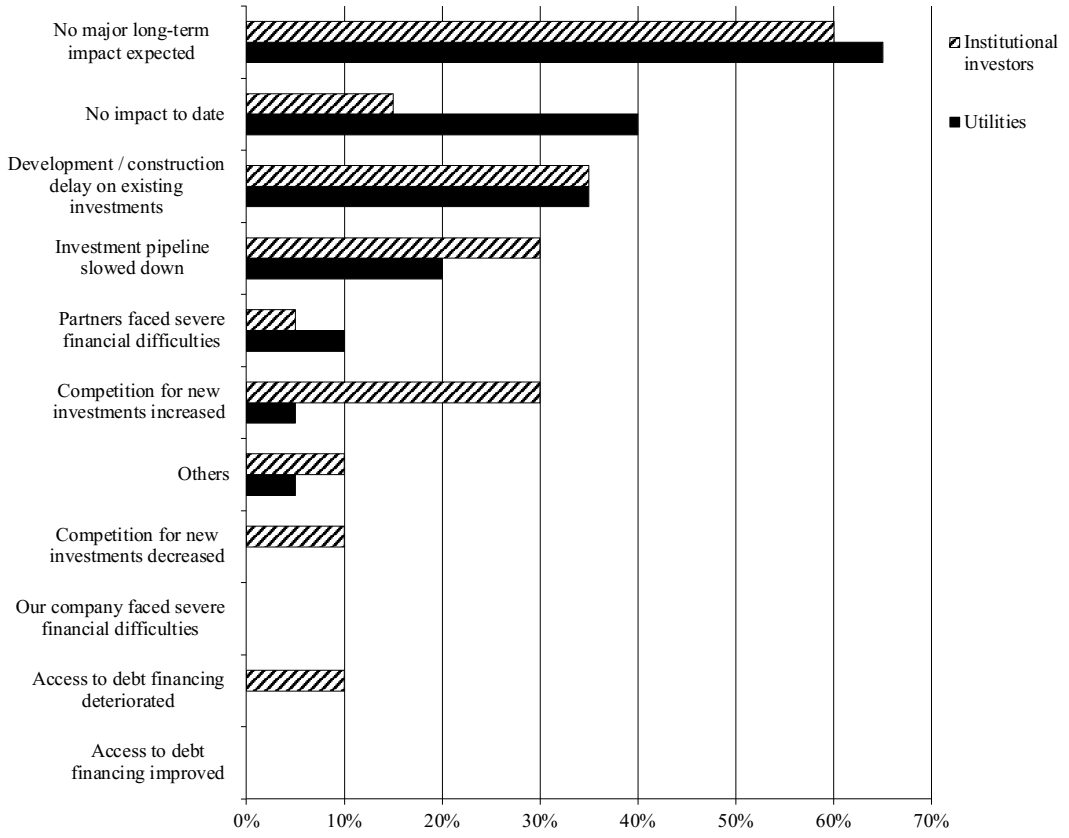


Figure A.2: Impact of the COVID-19 pandemic on investment in clean energy technologies (multiple answers possible, N=20 / N=20).

Table A.2: Most important reasons for investing in renewable energy and energy storage (one answer per factor possible), main barriers to investing in energy storage (one answer per factor possible), and expected number of revenue streams in future ESS business cases.

		Utility Companies (N=20)		Institutional investors (N=22)	
		1st Rank	2nd Rank	1st Rank	2nd Rank
Two most important sources of motivation for investing in clean energy technologies	Favourable return profile	50.0%	10.0%	40.9%	18.2%
	Synergy potential with existing resources	5.0%	0.0%	0.0%	4.5%
	Low return of comparable investments	0.0%	0.0%	4.5%	4.5%
	Replace existing technologies	10.0%	15.0%	0.0%	4.5%
	Improve carbon footprint	5.0%	10.0%	9.1%	9.1%
	Knowledge gain / experience	0.0%	10.0%	0.0%	0.0%
	Portfolio diversification	15.0%	30.0%	22.7%	18.2%
	Policy incentives	0.0%	0.0%	4.5%	4.5%
	Avoiding climate risk	5.0%	5.0%	4.5%	0.0%
	Capturing growth opportunities	5.0%	15.0%	4.5%	22.7%
	Others	5.0%	5.0%	0.0%	4.5%
Two most important barriers to energy storage investment	Comparably low returns	25.0%	25.0%	9.1%	18.2%
	No availability of viable business cases	25.0%	20.0%	40.9%	13.6%
	Lack of government support	5.0%	20.0%	18.2%	27.3%
	High technological risk	0.0%	5.0%	13.6%	18.2%
	Short investment horizon	0.0%	0.0%	0.0%	0.0%
	Long investment horizon	10.0%	5.0%	4.5%	0.0%
	Regulatory restrictions (e.g., Solvency II)	20.0%	0.0%	0.0%	0.0%
	No availability of smart IT infrastructure	5.0%	5.0%	0.0%	0.0%
	No free cashflow available	0.0%	0.0%	0.0%	9.1%
	Lack of external financing	0.0%	0.0%	0.0%	0.0%
	No experience in this field	5.0%	15.0%	13.6%	13.6%
	Others	5.0%	5.0%	0.0%	0.0%
Future ESS business cases	Include only one revenue stream	5.0%		9.1%	
	Include multiple revenue streams	95.0%		90.9%	

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Paper III. Preferences of homeowners for heat-pump leasing: Evidence from a choice experiment in France, Germany, and Switzerland[47]

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Abstract

While heat pumps are a promising solution for decarbonizing residential buildings, financial barriers often hinder their diffusion. Asset leasing – whereby service providers lease equipment and provide services in exchange for monthly payments – could help overcome some of the barriers to adoption. This study investigates homeowners' preferences for heat-pump leasing, examines their inclination to lease or purchase, and quantifies their willingness to pay for different services. Empirical insights are drawn from a discrete choice experiment conducted with 915 single-family homeowners who undertook 9,150 hypothetical leasing decisions in France, Germany, and Switzerland. Survey results show an interest in flexible, all-inclusive leasing offerings, especially in markets where heat pumps are at an early stage of diffusion. However, preferences for asset leasing differ between countries. German homeowners are the most open to leasing and would on average be willing to pay up to three times more than their French counterparts to shield themselves against technical risk. Given the role asset leasing could play in decarbonizing residential heat and enhancing energy security, policy makers may wish to adapt policy incentives to account for these service-based offerings.

Keywords: Asset leasing, Heat pumps, Business models, Choice experiment, Heating systems, Household decision-making.

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1. Introduction

Heat contributes to over 40% of global energy-related carbon dioxide emissions, and 46% of heat consumption occurs in buildings where supply relies heavily on fossil fuels (IEA, 2021a). Achieving the goal of net-zero emissions by 2050[49] requires considerable investment in low-carbon heating equipment for buildings. Heat pumps – devices that transfer thermal energy between spaces using electricity[50] – are a promising solution thanks to their low environmental impact, high energy-efficiency, and flexibility (Brockway and Delforge, 2018; Giambastiani et al., 2014; Howden-Chapman et al., 2009). To reach net zero, heat pumps would need to supply 20% of the global heat demand in buildings by 2030. This represents a sharp increase from the 7% observed today (IEA, 2021b). Beyond decarbonization, heat pumps have also recently garnered particular interest in Europe as a means of reducing dependence on oil and gas imports from Russia (European Commission, 2022; IEA, 2022). However, although the number of such installations has increased in the European Union (IEA, 2021c), only 6% of European residential buildings are heated using heat pumps (EHPA, 2021a).

Heat-pump adoption by homeowners is faced with several challenges – see Gaur et al. (2021). In particular, financial factors such as high prices relative to other energy sources as well as high investment costs are among the most important barriers (Pezzutto and Grilli, 2017). Access to sufficient capital at low cost is key for determining the economic viability of heat pumps. While extended mortgages may represent attractive financing solutions, many homeowners have limited borrowing capacity (Kelly et al., 2016). Given the important role heat pumps could play in the energy transition, several scholars have called for policy support or innovative financing solutions to increase their market uptake (Hlavinka et al., 2016; Karytsas, 2018; Raghavan et al., 2017).

Asset leasing – whereby a service provider leases an appliance and provides services to an end-user in exchange for monthly payments – could address some of the barriers faced by homeowners, thereby increasing heat-pump diffusion. Asset leasing is part of a broad category of service-based business models that emerged from the decentralization and servitization of business activities in the energy sector (Frei et al.,

[49] Several countries have pledged to achieve the net-zero emissions objective of balancing greenhouse gas emission production and removal from the atmosphere by mid-century in an effort to limit the rise in global temperature to well below 2°C compared to pre-industrial levels, and preferably to a maximum 1.5°C increase (UN, 2020).
[50] For example, devices that convert external heat sources such as air or water to heat that can be used for space heating and/or hot water supply. Heat pumps powered by renewable energy sources produce low-carbon heat.

2018). Service-based business models can be conceptualized as offerings in which financial, technical, performance, behavioural, and energy-price risks are all or in-part borne by service providers (Delta-EE, 2019).[51] Offerings can bundle various activities like advising, installing, and financing infrastructure, or managing assets through maintenance and repair activities (Helms, 2016). Revenue streams emerge from margins made on system installation, financing, and subscription-based contracts (IRENA, 2020). Since asset leasing removes upfront investment requirements and reduces risk and complexity for end-users, such offerings can enable the deployment of climate solutions in new market segments (Drury et al., 2012). Despite having been widely used to foster the diffusion of clean energy technologies like solar photovoltaic, notably in the United States of America (EPA, 2022), only a few companies offer heat-pump leasing in Europe.

One stream of research in the field of energy economics examines households' decision-making associated with heating systems, with studies diverging in terms of technological focus, geographical scope, household-specific or contextual aspects, and behavioural factors (Karytsas, 2018; Kikuchi et al., 2009; Leurent et al., 2018; Mahapatra and Gustavsson, 2008). While several scholars have investigated attitudes and preferences related to heating equipment purchasing (Achtnicht and Madlener, 2014; Ruokamo, 2016), empirical evidence concerning preferences for service-based offerings are scarce (Britton et al., 2021; Brown et al., 2022; Sovacool and Martiskainen, 2020). Sovacool et al. (2021) examined households' attitudes towards heat decarbonization in five European countries. The authors show that 18.9% of all survey respondents would be likely to consider asset leasing as a mean of delivering heating services. However, they do not provide insight into how preferences vary across different leasing offerings or countries. Similarly, Schleich et al. (2021) show that nearly a third of houseowner-occupiers in the United Kingdom would prefer to rent a heating system over owning it. They also show that homeowners prefer offerings that provide greater potential for energy savings and longer warranties. Since asset leasing could contribute to enabling the diffusion of heat pumps, there is a need to obtain a better understanding of how and to what extent different leasing offerings influence the willingness of house owners to pay for heating services in other countries.

[51] Financial risk relates to potential payment default by the end-user; technical risk pertains to equipment deficiencies or maintenance and repair activities; performance risk can be associated with appliances' efficiency and house-specific characteristics; behavioural risk emerges from end-users' heating habits (e.g., volume and timing of heat demand); energy price risk is linked to variability in wholesale electricity prices (Delta-EE, 2019).

We address this issue by presenting insights derived from a discrete choice experiment (DCE) conducted with 915 single-family house owners who made a total of 9,150 hypothetical heat-pump leasing decisions in France, Germany, and Switzerland. The objective was to clarify the latter's preferences for leasing offerings, examine their inclination to lease or purchase, and quantify their willingness to pay (WTP) for different services. We also shed light on the drivers and barriers associated with heat-pump adoption and leasing. We were particularly interested in these three countries because they exhibit interesting contrasts in terms of their level of reliance on oil and gas for residential heating, degree of heat-pump diffusion, and annual heat-pump-unit sales. German homeowners are highly reliant on fossil-fuel-fired boilers compared to their French and Swiss counterparts. While Switzerland has the highest degree of heat-pump diffusion among the three countries, France and Germany recently emerged as the first and third leading European markets for heat pump sales (see Subsection 3.1.1 for details). Hence, this case selection enables us to define implications for different market contexts.

To our knowledge, this study is the first to provide fined-grained empirical insight into homeowners' preferences for different heat-pump leasing offerings in multiple countries. Specifically, we show that asset leasing could contribute to decarbonizing residential heat, especially in markets where heat pumps are at an early stage of diffusion. Our findings contribute to the emerging academic research that investigates service-based business models for low-carbon heating. They are relevant for service providers as they shed light on best practices for the design of leasing offerings. Our insights could also serve as a basis for informing policy makers about policies that can enable the large-scale diffusion of heat pumps and thus the achievement of climate goals.

The remainder of this study is organized as follows: Section 2 describes the methodological approach and choice experiment design. Section 3 presents and discusses results. Section 4 summarizes the main findings, discusses implications for industry actors and policy makers, and suggests avenues for future research.

2. Methodology

We investigate single-family house owners' preferences for heat-pump leasing offerings and examine their inclination towards leasing or purchasing using a DCE. This approach builds on discrete choice and random utility theory (Manski, 1977; McFadden,

1974). It posits that products or services can be deconstructed into bundles of attributes, and that each attribute is associated with a specific level of utility. The total utility of a service equates to the sum of its parts' utilities, known as part-worth utilities. Individual stated preferences for service features are elicited by requiring participants to systematically choose a service offering from a set of hypothetical concepts that vary randomly according to different attributes. Participants are assumed to choose the services that would be likely to provide them with the highest utility. Part-worth utilities are estimated using choice modelling methods (Rao, 2014).

Choice experiments have been widely used by scholars to examine the preferences of households for clean energy products (Hille et al., 2018; Petrovich et al., 2019; Sagebiel et al., 2014), including heating appliances (Achtnicht, 2011; Meles et al., 2022; Rouvinen and Matero, 2013; Scarpa and Willis, 2010; Schleich et al., 2020). This strategy has the advantage of using a realistic setting for decision-making (Hill, 2017). Applying a stated-preference method is especially pertinent in this context given the scarcity of historical data on homeowners' decisions related to heat-pump leasing offerings (Louviere et al., 2000).

Next, we first describe the survey structure and provide a thorough account of the experiment design. We then present an overview of the data analysis methods employed in this study. Finally, we describe the data collection process and sample.

2.1. Survey development

Data were collected through an online survey which contained four sections. First, we asked single-family homeowners questions about their heating practices and preferences. This included questions about the types of heating systems installed in their house, the duration their main heating system had been in operation, their average annual heating costs, heating replacement plans, and the type of system they would be most likely to install if they were planning to replace their main heating system. Second, we asked DCE questions to elicit homeowners' stated preferences for heat-pump leasing offerings (see Subsection 2.2 for details). Third, we surveyed homeowners about the factors driving and hindering their preference for heat-pump installation and leasing. Fourth, we concluded the survey by gathering socioeconomic data (see Table A.1 and

A.2 in appendix). The survey also included a quality control to ensure that the observations of inattentive respondents were excluded.[52]

To facilitate comprehension and enhance completion rates, the survey was offered in French to respondents living in France or in the French-speaking part of Switzerland, and in German to respondents living in Germany or in the German-speaking part of Switzerland. The French and German questionnaires used euros (€) as currency, whereas the Swiss questionnaires used Swiss francs (CHF). The monetary values used in the choice experiment were also adapted to reflect country-specific market realities (see Subsection 2.2 for details). Hence, four versions of the questionnaire were developed using Sawtooth Software's module SSI Web. The questionnaires and DCE designs were pre-tested with 12 experts and homeowners to verify their adequacy and intelligibility. Adjustments were made accordingly prior to the fieldwork.

2.2. Experimental design

The DCE comprised two sections: an introductory part followed by ten randomized choice tasks. First, we asked homeowners to imagine that they were planning to replace their heating system the following year and were considering installing an air-to-water heat pump. We also asked them to assume that the heat pump could be installed in their house. We explained that the device would use electricity to take thermal energy from the outside air to heat water and indoor spaces, and that it had an expected service life of 15 years. Further, we told homeowners that they had the option to lease the heat pump by making fixed monthly payments for the duration of the leasing contract – namely, 15 years. We informed them that at the end of the lease agreement they would become the owner of the heat pump. Additionally, we pointed out that if they moved before the contract ended, they could transfer the lease to the new homeowner or terminate it by paying the balance of what was owed on the heat pump and installation costs. We also specified that the contract did not include the cost of the electricity needed to operate the heat pump. At the end of this introductory part, we informed homeowners that their leasing options varied according to the attributes presented in Table 1. These factors were chosen as they represent important considerations in heating system procurement decisions.

[52] The quality-control measure consisted of an attention check and was designed following Petrovich et al. (2021).

Table 1: Attributes and attribute levels manipulated in the choice experiment.

Attributes	Description	Attribute levels
Monthly lease payment	Monthly payments homeowners pay to lease the heat pump and benefit from services (in CHF or €).	- 195 CHF or 130 € - 230 CHF or 155 € - 265 CHF or 180 €
Type of leasing contract	Equipment and services included in the lease agreement.	- Basic package: Heat pump and installation costs included - Maintenance package: Heat pump, installation, and yearly maintenance costs included - All-inclusive package: Heat pump, installation, yearly maintenance, repair, and replacement part costs included
Service provider	Type of actor providing the services.	- Heat pump manufacturer - Local energy utility - Heating specialist

The attribute *monthly lease payment* referred to what homeowners needed to pay to lease the heat pump and benefit from certain services. We specified three levels – namely, 130 €, 155 €, and 180 € in the French and German surveys, and 195 CHF, 230 CHF, and 265 CHF in the Swiss survey. Monthly payments were calculated by drawing on prior studies and researching market-specific prices for air-to-water heat pumps as well as installation, maintenance, and repair activities. We also discussed this design with industry actors and experts to test their accuracy, along with the overall DCE design. Defining such levels enabled us to estimate homeowners' WTP for different heat-pump leasing features as specified by the other attributes.

The attribute *type of leasing contract* described the elements included in the lease agreement and comprised three levels. The basic package included the heat pump and installation costs. The maintenance package comprised the costs included in the basic package as well as yearly maintenance fees. The all-inclusive package included the heat pump, installation, maintenance, and all potential repair or replacement costs. This design enabled us to compute WTP estimates for maintenance and repair services.

Finally, the attribute *service provider* specified the type of actor providing the services. This included a heat pump manufacturer, local energy utility, and heating specialist. Research has shown that several actors can provide heating services, and that specific actors may be preferred in certain countries (Schleich et al., 2021). These levels allow us to examine if and to what extent French, German, and Swiss homeowners differentiate between different service providers.

In the second section of the DCE we presented ten consecutive two-stage choice tasks to homeowners: 1) preferred leasing model, and 2) preference between leasing and purchasing. First, we displayed three heat-pump leasing concepts simultaneously in each choice task and invited respondents to select their preferred offering (see Figure 1). To mitigate the hypothetical bias, we instructed homeowners to make their choices as if these were real-life decisions and to consider how this would affect their budget (Hensher, 2010). The heat-pump leasing concepts varied randomly without any prohibition according to the attributes and levels described in Table 1. Respondents could revisit these definitions at any time during the choice tasks by scrolling their pointer over the attribute and levels of each leasing concept to avoid confusion or misinterpretation. We used a symmetrical DCE design to avert the number-of-levels effect, whereby attributes with more levels are awarded higher importance scores than other attributes (Wittink et al., 1992).

	Leasing option 1	Leasing option 2	Leasing option 3
Lease payment per month	265 CHF	195 CHF	265 CHF
Type of lease contract	Maintenance package	All-inclusive package	All-inclusive package
Service provider	Local energy distributer	Heat pump manufacturer	Heating specialist
	○	○	○

Figure 1: Example of heat-pump leasing concepts displayed to homeowners.

Once homeowners had selected their preferred leasing option, we asked them in a second stage to imagine that they now also had the option to purchase the heat pump for a specific price, paid upfront. We explained that the purchasing price included the installation costs and a two-year warranty, but no maintenance.[53] We then instructed respondents to indicate if they would prefer to lease the heat pump as they had indicated in the first part of the choice task, or would rather purchase it.

This multi-stage design enabled us to first focus on the trade-offs homeowners make when choosing heat-pump leasing offerings by testing several concepts simultaneously. It also provided us with additional information regarding adoption intentions (Orme, 2016). To ensure the adequacy of our choice experiment, we generated an efficient DCE

[53] The purchasing prices shown to respondents were the same as the price assumptions used to derive the lease payment per month levels.

design using Sawtooth Software.[54] We also included three manipulation checks at the end of the choice experiment to control if respondents had understood the choice situation correctly.[55] The DCE design was also validated using inputs from practitioners.

2.3. Model specification and willingness-to-pay estimates

We estimated part-worth utilities associated with different features of heat-pump leasing offerings by specifying Hierarchical Bayes (HB) models. HB models are widely used to investigate consumer behaviour as their hierarchical structure enables information to be extracted from two levels (Allenby et al., 2005). At the lower level, the probability of each individual houseowner to choose specific heat-pump leasing offerings is specified by a multinomial logit model. At the higher level, individual choices are described by a multivariate normal distribution expressed by a mean vector and variance-covariance matrix. The latter model describes the heterogeneity of preferences across the sample (Orme and Howell, 2009). This modelling approach enabled us to address any lack of information at the individual level by collecting information across respondents.

In line with prior research, we used the root likelihood (RLH) parameter as a measure of the goodness-of-fit between part-worth utility estimates and the choices made by homeowners (Côté et al., 2022; Salm et al., 2016). RLH represents the geometric mean of all estimated probabilities. It is computed by taking the n^{th} root of the likelihood that homeowners would make the decision that they actually made in each task, with n corresponding to the total number of choices they made in all tasks (Orme, 2016). High RLH values indicate a good fit between the data and model, with RLH = 1 being the highest possible value. In our DCE, homeowners were presented with three heat-pump leasing concepts to choose from. The predictability of homeowners' decisions based on chance is thus 1/3 = 0.33. Since the average RLH values computed for the three models are more than twice that of the level of chance (RLH_{France} = 0.678; $RLH_{Germany}$ = 0.672;

[54] The *Test Design* function simulates homeowner responses, performs a logit run, and reports standard error estimates as well as a D-efficiency value. Our design is in accordance with the guidelines for efficient CBC (Sawtooth Software, 2022).

[55] We designed the manipulation checks based on Schleich et al. (2021). The latter consisted of three items regarding which respondents were asked to indicate if a statement was "true," "false," or they did not know ("I don't know"). Statements were adapted to the context of this study and formulated as follows: 1) "after 15 years of leasing, the heat pump will belong to you," 2) "if you move before the end of the 15-year leasing contract, the new houseowner will be forced to take over the leasing contract," and 3) "if you lease the heat pump, you will have to pay monthly payments."

$RLH_{Switzerland} = 0.685$), we can assume a good fit between the data sets and models (Hille et al., 2018).

Finally, we calculate implicit WTP values using part-worth utility estimates following Kaenzig et al. (2013). WTP estimates correspond to the upper limit of the amount homeowners would be willing to pay for a heat-pump leasing offering that has a preferred feature compared to an offering with the least preferred feature. In this way, any upgrade relative to the least preferred option can be ascribed a monetary value.

2.4. Data collection and sample

The survey was fielded between February and March 2022 by a market research institute using respondent panels representative of the French, German, and Swiss general populations. Single-family house owners were specifically targeted as they are more likely to make decisions about heating system replacement than tenants, especially in the case of heat pumps, as installation activities may require considerable retrofitting work. Single-family house owners were recruited using a precise screening rule and by stratifying survey invitations to match the distributions of national populations according to sex, age, income, level of education, and region.[56] Only respondents who fulfilled our selection criteria were directed to the survey. We first conducted a soft launch with 29 Swiss homeowners to further test the questionnaire and analyse initial responses. Since our preliminary observations were satisfactory, we proceeded with the final implementation of the Swiss survey. Data collection in France and Germany followed the same sequential approach. Homeowners took on average 17 min to complete the questionnaire and received tokens exchangeable for goods or services as compensation for their participation.

A total of 1,582 single-family house owners who fulfilled our selection criteria accessed the survey (see Table 2). Responses from homeowners who failed the quality control (149) or who provided incomplete responses (456) were excluded. Additionally, observations from ‘speeders’ who completed the survey in less than half of the median response time achieved by their national subgroup (62) were also removed from the sample. The final sample includes insights from 915 single-family house owners who

[56] The selection question was: “*Do you own a single-family house?*” Only respondents who answered ‘yes’ to this question were provided access to the survey. The quota questions were designed according to five variables – namely, age, sex, level of education, income, and region. See Table A.1 in the appendix for details.

conducted an aggregated 9,150 hypothetical heat-pump leasing decisions. Homeowners in national subsamples mostly follow the same distribution as the general populations in terms of sex and region (see Table A.1 in appendix). However, their household monthly income appears to be higher than that of the general population, and they are older, on average. These trends accord with what has been observed in several countries (Andrews and Sánchez, 2011). Regarding their level of education, homeowners in the French subsample have a higher level of education than the general population. Similarly, homeowners tend to have a higher level of education than the general population in other countries. However, the distribution in the German and Swiss subsamples largely followed that of the respective national populations.[57]

Table 2: Survey response funnels (number of respondents and response rates).

	French subsample		**German subsample**		**Swiss subsample**		**Final sample**	
	No. of resp.	Resp. rate	No. of resp.	Resp. rate	No. of resp.	Resp. rate	No. of resp.	Resp. rate
Survey accessed	581		472		529		1,582	
Incomplete responses	171	29.4%	99	21.0%	186	35.2%	456	28.8%
Failed attention check	86	14.8%	41	8.7%	22	4.2%	149	9.4%
Survey completed	324	55.8%	332	70.3%	321	60.7%	977	61.8%
Speeders (<1/2 median)	20	3.4%	24	5.1%	18	3.4%	62	3.9%
Final sample	304	52.3%	308	65.3%	303	57.3%	915	57.8%

3. Results and discussion

First, we present descriptive results about homeowners' heating practices and intentions. We then shed light on the perceived drivers and barriers associated with heat-pump installation and leasing. This enables us to gain a better understanding of homeowners' decision-making. Second, we describe the results of the first part of the DCE by showing part-worth utility estimates and discussing preferences for heat-pump leasing offerings. Third, we present the results of the second part of the DCE and explore differences in preferences between leasing and purchasing. Fourth, we delineate

[57] The compositions of our national subsamples varied. The cross-country comparison results presented in Section 3 are not designed to specify causal relationships. Rather, they provide rich descriptive insights into different market realities and allow us to define important implications for service providers and policy makers.

importance score estimates and examine the relative weight of attributes in leasing decisions. Finally, building on the part-worth utilities, we include WTP estimates for national subgroups. This allows us to clarify how and to what extent different heat-pump leasing offerings influence homeowners' willingness to pay.

3.1. Descriptive results

3.1.1. Heating practices and intentions

A considerable share of homeowners rely on fossil fuels for heating. Nearly 39.1% of French, 80.8% of German, and 52.1% of Swiss respondents used natural gas or oil to heat their single-family houses (see Figure 2). These values are in line with the shares of national residential building stocks that rely on these fuels for heating.[58] In contrast, fewer homeowners claimed to use a heat pump (18.8%, 8.8%, and 33.7% of French, German, and Swiss homeowners, respectively), although the technology appears to be most widely used by Swiss homeowners. This could be explained by their greater affluence (see Table A.1 in appendix) and the relatively low carbon-intensity of the electricity mix in Switzerland compared to Germany. However, these values are relatively higher than the level of heat pump deployment observed in national residential building stocks.[59] Differences between the degree of diffusion in single-family houses and multi-family buildings may partly explain this deviation (Cauret, 2021). Hence, our results underscore the dependence of these countries on fossil fuels for residential heating, particularly in Germany, and reflect different stages of heat-pump diffusion.

[58] The share of residential buildings that rely on gas or oil as a primary energy source for heating is 52.3% in France (2020), 75.7% in Germany (2018), and 60.1% in Switzerland (2017) (BFS, 2018; Destatis, 2021; SDES, 2021).

[59] Nearly 1.9% of German residential buildings are heated using ground or other ambient heat (2018), whereas 9.7% (2020) and 17.9% (2017) of French and Swiss buildings use heat pumps, respectively (BFS, 2018; Destatis, 2021; SDES, 2021).

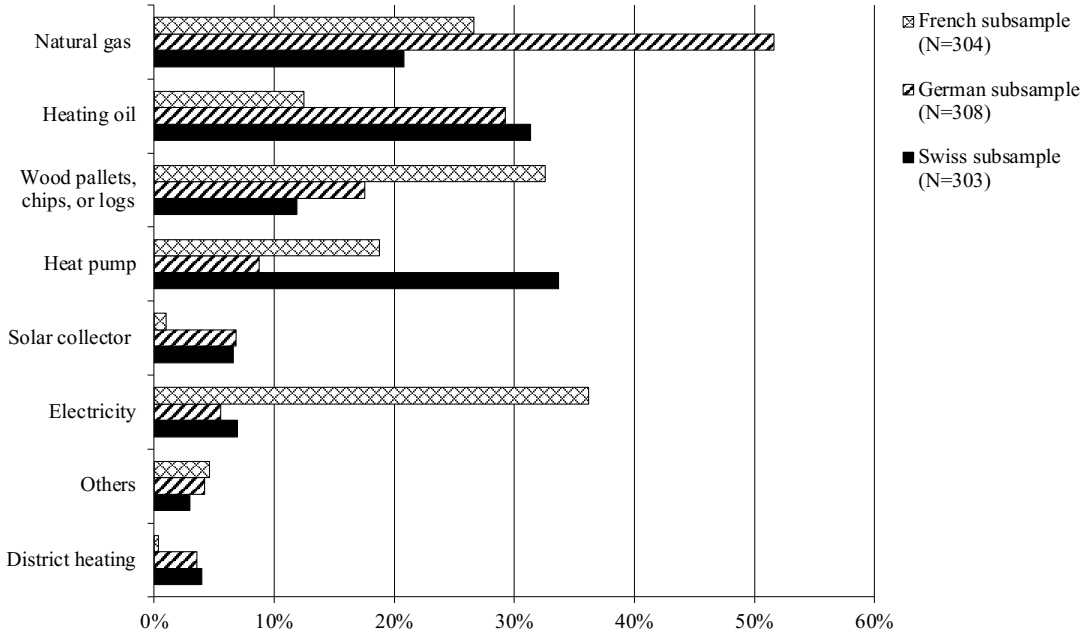


Figure 2: Share of respondents per type of energy source(s) used for heating (multiple answers possible).

Most homeowners have the intention to adopt a low-carbon heating system, with heat pumps having the potential to become the dominant technology in the three countries. Considerable shares of homeowners stated that they would most probably install a heat pump if they were planning to replace the main heating system in their house – 40.8%, 30.5%, and 58.4% of French, German, and Swiss homeowners, respectively (see Figure 3). Altogether, 25.8% of these homeowners (N=395) foresaw doing so within the next five years. This apparent interest in heat-pump adoption is reflected in recent developments, concerning which France and Germany emerged as the first and third leading European markets for heat-pump-unit sales, respectively (EHPA, 2021b). These developments can be explained by the general ubiquity of electrical heating in France, and the absolute size of the heat pump market in Germany (Lowes et al., 2022). Indeed, our results show that the share of French homeowners who use electrical heaters could plummet – a fall partly driven by high operational costs (MTE, 2021). Homeowners may thus be keen to move from electrical heaters to more efficient electric heat pumps (Lowes et al., 2022), although a trend toward the adoption of solar collectors may also be observed.

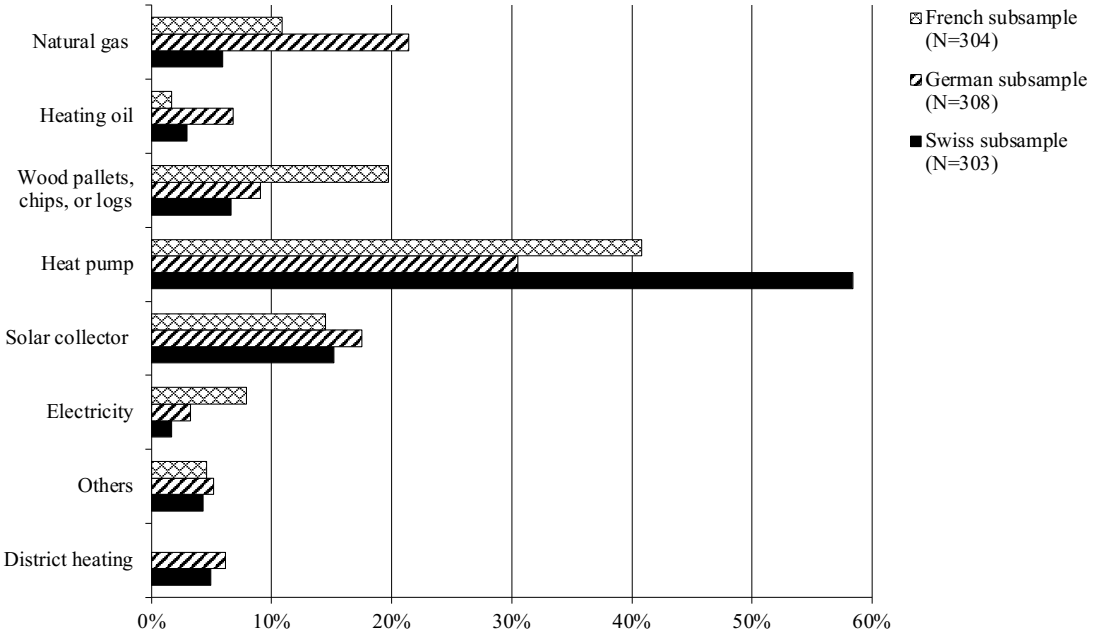


Figure 3: Share of respondents per type of energy source they would most probably choose if they were planning to replace the main heating system in their house (one answer possible).

Further, 12.5% of French, 28.2% of German, and 8.9% of Swiss homeowners would probably choose to install a natural-gas-fired or oil-fired boiler if they replaced their current heating system (see Figure 3). Given that most homeowners do not plan to replace their main heating system in the near future and that domestic boilers can have a lifespan of well over 20 years (see Table A.2 in appendix), a considerable share of households could still be using fossil fuels for heating in 2050. To avoid this scenario and ensure the attainment of the net-zero goal, the International Energy Agency recently urged countries to implement bans on new fossil-fuel-fired boiler sales from 2025, except for hydrogen-ready boilers (IEA, 2021d). Similarly, several scholars have also stressed the necessity of a prompt phase-out of fossil-fuel heating and called for more stringent policies in these jurisdictions (Frank and Quitzow, 2022; Lowes et al., 2022; Nägeli et al., 2020). Both carrot and stick policies such as financial incentives, regulations, and even prohibitions have been shown to play an important role in accelerating the decarbonization of heat (Chaudry et al., 2015; Kerr and Winskel, 2021). However, despite the introduction of financial incentives and the tightening of

regulations for buildings in the respective countries, none are planning an outright ban on the sale or installation of fossil-fuel heating before the middle of the present decade.[60]

3.1.2. Heat-pump adoption and leasing: Drivers and barriers

Environmental protection and energy security are key drivers of heat-pump adoption, along with hedging against fossil fuel price volatility and benefiting from financial incentives. A considerable share of homeowners view reducing their environmental impact and dependence on foreign energy sources as being the most important factors in favour of heat-pump installation (see Table 3). These findings support studies which show that heating decisions are driven by aspirations to deal with external threats like environmental degradation or dependence on fossil fuels (Achtnicht, 2011; Michelsen and Madlener, 2016, 2012). While hedging against energy price increases was also highlighted as a determinant of heat-pump installation by German and Swiss homeowners, access to subventions and tax benefits emerged as a key driver for French homeowners. Perhaps this can be explained by the recent increases in the price of natural gas in Europe, on which German homeowners are strongly reliant (Bloomberg, 2022). It may also be attributed to the introduction of attractive incentives to promote low-carbon heating in France – see Bercy Infos (2022) and Kerr and Winskel (2021). For example, the *MyPrimeRenov* scheme that was introduced in 2020 provides capital payments based on household revenue. Scholars have shown that incentives play a key role in investment decisions (Mahapatra and Gustavsson, 2008), and that beyond cost reductions, homeowners value obtaining subsidies as such (Schleich et al., 2022). Since most of the policy focus has so far been on facilitating equipment purchase (Tognetti, 2020), some scholars suggest adapting incentives to account for service-based offerings (Schleich et al., 2021).

[60] In France, a carbon-efficiency threshold of 4 $kgCO_2/m^2/yr$ was introduced in January 2022 to limit emissions from new single-family houses (MTE, 2021). Heating equipment that relies exclusively on fossil fuels is de facto excluded. This limit may be reduced by up to 40% until 2030 (ECOS, 2021). Further, oil-fired boiler and coal furnace installation will be prohibited from July 2022, unless it is technically unfeasible to do otherwise (Direction de l'information légale et administrative, 2022). In Germany, the installation of mono-fuelled oil or coal systems will be prohibited in all buildings from 2026, unless the installation of cleaner alternatives is impossible (Braungardt et al., 2021; Bundesregierung, 2020). The same restrictions will apply to new fossil-fuel-fired boilers (BMI, 2021). An obligation to use renewable energies will also be imposed for new buildings (Braungardt et al., 2021). In Switzerland, there is currently no nationwide ban on oil or gas-fired heating systems, but combustion boiler emissions are restricted (Bundesrat, 2021). A tightening of energy standard regulations for buildings can nonetheless be observed in several cantons, including restrictions or even bans on certain types of installation (Direction de l'énergie, 2021; SWI, 2021). For example, Basel-City, Glarus, and Zurich recently adopted a legislation that bans fossil-fuel heating, although deadlines and specific conditions vary.

Table 3: Drivers of and barriers to heat-pump adoption and leasing.

Variable name	Description	% in French subsample (N=304)	% in German subsample (N=308)	% in Swiss subsample (N=303)
Drivers of heat-pump adoption	*Three most important factors in favour of heat-pump installation (three answers required).*			
	Reducing impact on the environment	**59.2%**	**56.2%**	**75.2%**
	Access to subventions and / or tax benefits	**50.0%**	22.1%	24.1%
	Decreased dependence on foreign energy sources	**44.1%**	**60.7%**	**49.8%**
	Hedging against potential price increases in energy sources	37.8%	**48.4%**	**37.3%**
	Relatively low operating costs	34.2%	40.3%	35.0%
	Increased home value	30.9%	22.7%	24.8%
	Staying at the frontier of technological innovation	24.3%	34.7%	26.1%
	Positive experience of heat pump owners in surrounding	18.1%	12.0%	24.4%
	Others	1.3%	2.9%	3.3%
Barriers to heat-pump adoption	*Three most important factors hindering heat-pump installation (three answers required).*			
	Relatively high purchase price	**86.5%**	**76.0%**	**75.6%**
	Lack of funds to pay the purchase price	**49.7%**	46.1%	**50.8%**
	Operation and maintenance concerns	**41.1%**	**46.8%**	**42.9%**
	Uncertain performance	40.5%	**51.9%**	38.3%
	High complexity of projects	33.9%	27.9%	30.7%
	Lack of subvention or tax benefits	26.3%	30.5%	34.3%
	Negative experience of heat pump owners in surrounding	14.8%	12.0%	9.9%
	Decreased home value	4.3%	3.2%	2.3%
	Others	3.0%	5.5%	15.2%
Drivers of heat-pump leasing	*Two most important factors in favour of heat-pump leasing (two answers required).*			
	No upfront investment required (purchase price)	**79.3%**	**74.0%**	**85.1%**
	Simplicity of all-inclusive packages	**60.9%**	**70.1%**	**58.4%**
	Possibility to transfer the leasing contracts to new homeowners	25.7%	13.0%	21.1%
	Attractive financing rates	23.7%	30.5%	17.8%
	Unavailability of other financing solutions	9.5%	10.4%	13.9%
	Others	1.0%	1.9%	3.6%
Barriers to heat-pump leasing	*Three most important factors hindering heat-pump leasing (two answers required).*			
	The length of the lease agreement	**59.2%**	**51.6%**	**55.8%**
	Additional costs	**56.6%**	42.9%	**47.9%**
	Potential challenges with transferring the lease to new owners	29.3%	28.2%	32.3%
	Third-party ownership	27.3%	**43.5%**	43.6%
	The complexity of the lease agreement	26.3%	31.8%	16.8%
	Others	1.3%	1.9%	3.6%

Financial and technical factors are the most important barriers to heat-pump adoption. A considerable share of homeowners view the high purchase price as well as operation and maintenance concerns as being the most important barriers to heat-pump installation. While a lack of available funds is also highlighted as an impediment by French and Swiss homeowners, uncertainty regarding the performance of heat pumps is a major hinderance for German homeowners. These results corroborate the findings of

scholars who claim that financial factors are the most important barriers to adoption (Pezzutto and Grilli, 2017). Further, they suggest a certain lack of confidence in the technology, particularly in Germany where the degree of heat-pump diffusion is considerably less.

Heat-pump leasing could contribute to mitigating risks for end-users. Most homeowners foresee the main benefit of such offerings as being the elimination of upfront investment requirements and the simplification of maintenance and repair activities. However, the length of leasing agreements generally appears to constitute an important drawback, pointing to the desirability of offering homeowners flexible leasing contracts. For example, this could be achieved by including an option for homeowners to purchase the heat pump at any point in time, similarly to a lease-to-own model. Further, other service-based offerings such as efficient asset leasing – which in addition would mitigate performance-related risk for end-users – could contribute to overcoming some of the barriers to heat-pump diffusion. This may be particularly relevant in Germany, where uncertainty about performance appears to be of concern.

3.2. Preferences for heat-pump leasing

Preferences for heat-pump leasing offerings are investigated by specifying three country-specific HB models using 9,150 hypothetical leasing decisions made by 915 single-family house owners (see Table 4). Part-worth utility estimates indicate the relative preferences homeowners associate with specific features and were zero-centred to enable within-attribute comparisons. Unsurprisingly, results show that homeowners tend to prefer offerings with lower *monthly lease payments*, as the lowest level of this attribute is associated with the highest level of utility across the three national subsamples. However, Swiss homeowners appear to be less reluctant than their French and German counterparts to lease a heat pump for higher monthly payments as the spread between their part-worth utilities is significantly smaller ($p < 0.01$ – see Table A.3 in appendix).

Table 4: Zero-centred utility, lower and upper 95% confidence interval, and standard deviation estimates.

		HB model French homeowners (N = 304)			HB model German homeowners (N = 308)			HB model Swiss homeowners (N = 303)		
Attribute	**Attribute levels**	**Zero-centred utility**	**Lower and upper 95% confidence interval**	**Standard deviation**	**Zero-centred utility**	**Lower and upper 95% confidence interval**	**Standard deviation**	**Zero-centred utility**	**Lower and upper 95% confidence interval**	**Standard deviation**
Monthly lease payment	130 € (or 195 CHF)	51.74	[46.75; 56.73]	44.39	51.46	[46.75; 56.17]	42.13	44.21	[38.97; 49.45]	46.52
	155 € (or 230 CHF)	10.13	[7.68; 12.58]	21.82	5.38	[3.29; 7.47]	18.72	1.77	[–0.17; 3.70]	17.16
	180 € (or 265 CHF)	–61.87	[–66.68; –57.06]	42.79	–56.84	[–61.43; –52.26]	41.06	–45.98	[–50.78; –41.18]	42.62
Type of lease contract	Basic package	–53.61	[–57.73; –49.49]	36.63	–50.63	[–54.76; –46.49]	37.00	–47.98	[–52.14; –43.81]	37.01
	Maintenance package	16.06	[13.48; 18.64]	22.98	–8.24	[–10.36; –6.11]	19.03	–4.40	[–7.04; –1.76]	23.45
	All-inclusive package	37.55	[34.32; 40.78]	28.74	58.86	[54.53; 63.20]	38.83	52.38	[48.04; 56.71]	38.49
Service provider	Heat pump manufacturer	3.19	[–0.35; 6.73]	31.47	–8.43	[–11.33; –5.53]	25.98	–0.65	[–4.81; 3.51]	36.93
	Local energy utility	–11.80	[–15.95; –7.65]	36.91	1.55	[–2.04; 5.13]	32.12	1.90	[–2.89; 6.70]	42.63
	Heating specialist	8.61	[4.71; 12.51]	34.71	6.88	[3.42; 10.35]	31.01	–1.25	[–5.47; 2.96]	37.44
None		158.79	[112.84; 204.74]	408.76	10.46	[–24.16; 45.07]	309.94	255.12	[212.95; 297.29]	374.51

Regarding the *type of lease contract* attribute, homeowners prefer all-inclusive packages in which the cost of the heat pump, its installation, yearly maintenance, and potential repairs and part replacements are included. This may be explained by the fact that such packages could contribute to addressing operation- and maintenance-related concerns, which are viewed as some of the most important barriers to heat-pump installation (see Subsection 3.1.2). Further, these results suggest that homeowners may perceive the risk of technical failure to be high. This appears to be especially true of German and Swiss homeowners as the spread between their part-worth utilities is significantly higher than for French homeowners ($p < 0.01$ and $p < 0.05$, respectively – see Table A.3 in appendix).

As for the *service provider* attribute, preferences seem to diverge between countries. While French and German homeowners tend to favour obtaining the services of a heating specialist, Swiss homeowners appear to favour a local energy utility. However, Swiss homeowners do not seem to differentiate much between providers, as the spread between their part-worth utilities is small. Further, the relatively large standard deviations associated with this attribute indicate a high level of heterogeneity among preferences. These findings differ from those of earlier research which showed that British homeowners would be more inclined to rent a heating system from an equipment manufacturer, followed closely by an energy utility (Schleich et al., 2021). This suggests that having several types of providers that offer heat pump services, alone or in collaboration, may be desirable for meeting the preferences of a wider range of end-users.

To investigate the robustness of our DCE results, we conducted a series of additional analyses. First, we specified country-specific HB models using only the responses of homeowners who had correctly passed the three manipulation checks by following the approach described in Subsection 2.3. We then carried out Mann-Whitney *U* tests to examine if the mean part-worth utility estimates of attribute levels varied significantly between the full models and curtailed ones (see Table A.4 in appendix). Since the results of the curtailed subsamples are largely similar to the ones found for the full national subsamples, we can assume that our DCE results are not affected by the inclusion of those who provided inexact answers to the manipulation checks. This holds true for all models except for in the case of Switzerland, where respondents in the curtailed subsample appear to have a slight preference for services obtained from a heat pump manufacturer. This can be explained by the fact that Swiss homeowners do not

differentiate much between service providers and that their preferences are rather heterogeneous.

Second, we specified additional HB models, this time retaining only responses from homeowners who stated that they planned to replace their main heating system with a heat pump. Mann-Whitney *U* test results confirm that the preferences of these homeowners mainly match the ones for the full subsamples, except for in the case of the service provider (see Table A.4 in appendix). French and Swiss homeowners who planned to install a heat pump appear to be slightly more inclined to procure the services of a manufacturer. This further underlines the relevance of having different types of service providers on the market to meet the preferences of different end-users.

3.3. Preferences related to leasing and purchasing

The results of the second part of the DCE suggest a certain interest in heat-pump leasing, although to a different extent across countries. French homeowners planning to replace their heating system with a heat pump favour leasing rather than purchasing in 49.6% of cases (N=1,240).[61] In contrast, Swiss homeowners appear to be less inclined to lease heat pumps as they chose to do so in only 33.3% of cases (N=1,770). As argued in Subsection 3.1.1, this may be explained by their greater average affluence. Interestingly, German homeowners seem to be the most open to asset leasing, as they chose to lease the heat pump in 63.6% of cases (N=940). These results could be explained by the fact that Germans tend to rent more than the French, with 49.6% of the German population living in rented houses compared to 36% in France – although, Switzerland has the lowest homeownership rate in Europe, with 57.7% of Swiss living in rental housing (Eurostat, 2022). Further, German homeowners are more concerned about maintenance and operational performance (see Subsection 3.1.2). Scholars have shown that end-users who worry about such factors are more inclined to lease equipment (Rai et al., 2016).

Additionally, our results show that most homeowners tend to have strong preferences for either leasing or purchasing. Indeed, 19.8% of Swiss homeowners planning to install a heat pump preferred leasing in all choice tasks, as opposed to 55.9% who expressed a

[61] In this case, "N" does not refer to the number of respondents, but rather to the number of choice tasks – i.e., the number of times respondents had to choose between leasing or purchasing a heat pump.

strong and unanimous preference for purchasing (see Figure A.1 in appendix). In contrast, 44.7% of German homeowners systematically chose leasing, and 24.5% purchasing. A similar distribution can be observed in the case of respondents from France, where most homeowners chose only leasing (33.9%) or purchasing (40.3%). These findings support the claim that attitudes towards asset leasing are rather polarized across countries. They also reiterate the relevance of leasing offerings, especially in Germany where heat pumps are at an early stage of diffusion and technical risk is perceived to be high. Research has shown that a peer effect (or lack thereof) is determinant for households' clean energy adoption decisions, as this may reduce (increase) intrinsic uncertainty (Rai et al., 2016).

3.4. Average importance of attributes in leasing decisions

Average importance scores were computed to estimate the relative weight each attribute has in heat-pump leasing decisions. Importance scores represent the difference in part-worth utilities between the most and least preferred levels for a given attribute, divided by the sum of differences in all attributes (Salm and Wüstenhagen, 2018). Results show that the *monthly lease payment* attribute has an important weight in heat-pump leasing decisions, especially for French and German homeowners – 43.9% and 40.9%, respectively (see Table 5). These findings support research which shows that cost is the most important factor in homeowners' decisions about heating systems (Rouvinen and Matero, 2013). The *type of lease contract* also plays an important role, particularly for German and Swiss homeowners who award relatively more importance to this factor (40.1% and 38.0%, respectively) than French homeowners (34.4%). In contrast, the type of *service provider* seems to be assigned considerably less weight in leasing decisions, especially for French and German homeowners (21.8% and 18.9%, respectively) as opposed to Swiss ones (24.8%). Mann Whitney *U* test results confirm these significant distinctions.

Table 5: Average importance scores (AIS), standard deviations (SD), and Mann Whitney *U* test (2-tailed) results, by attribute.

	French subsample (N=304) (1)		German subsample (N=308) (2)		Swiss subsample (N=303) (3)		*P*-value[a] for difference test between (1) and (2)		*P*-value[a] for difference test between (1) and (3)		*P*-value[a] for difference test between (2) and (3)	
Attribute	**AIS (%)**	**SD (%)**	**AIS (%)**	**SD (%)**	**AIS (%)**	**SD (%)**						
Monthly lease payment	43.88	20.0	40.93	20.4	37.19	20.4	0.078	*	0.000	***	0.020	**
Type of lease contract	34.37	17.0	40.14	19.6	38.01	18.1	0.001	***	0.013	**	0.272	
Service provider	21.75	16.7	18.93	14.2	24.80	17.5	0.108		0.017	**	0.000	***

[a] *** Significance level of 1% ($p < 0.01$), ** Significance level of 5% ($p < 0.05$), * Significance level of 10% ($p < 0.1$).

3.5. Willingness to pay for heat pump services

We calculated implicit WTP values to estimate the upper limit of the amount homeowners would be willing to pay for heat-pump leasing offerings that include a preferred feature instead of the least preferred one. Figure 4 shows aggregated WTP estimates. WTP values of zero indicate the least preferred feature of an attribute, as specified in Subsection 3.2. French homeowners would be willing to pay up to 8.98 € per month to obtain the services of a heating specialist instead of a local energy utility, and 6.59 € for a heat pump manufacturer. Similarly, German homeowners would pay up to 7.07 € monthly to move from an agreement with a heat pump manufacturer to one concluded with a heating specialist, and 4.61 € for a local utility. In contrast, Swiss homeowners would only be willing to pay up to 2.45 CHF per month to benefit from the services of a local utility rather than a heating specialist, and 0.47 CHF for a heat pump manufacturer. These findings reiterate the relevance of having different types of actors providing services in markets, although this appears to be less critical for Swiss homeowners.

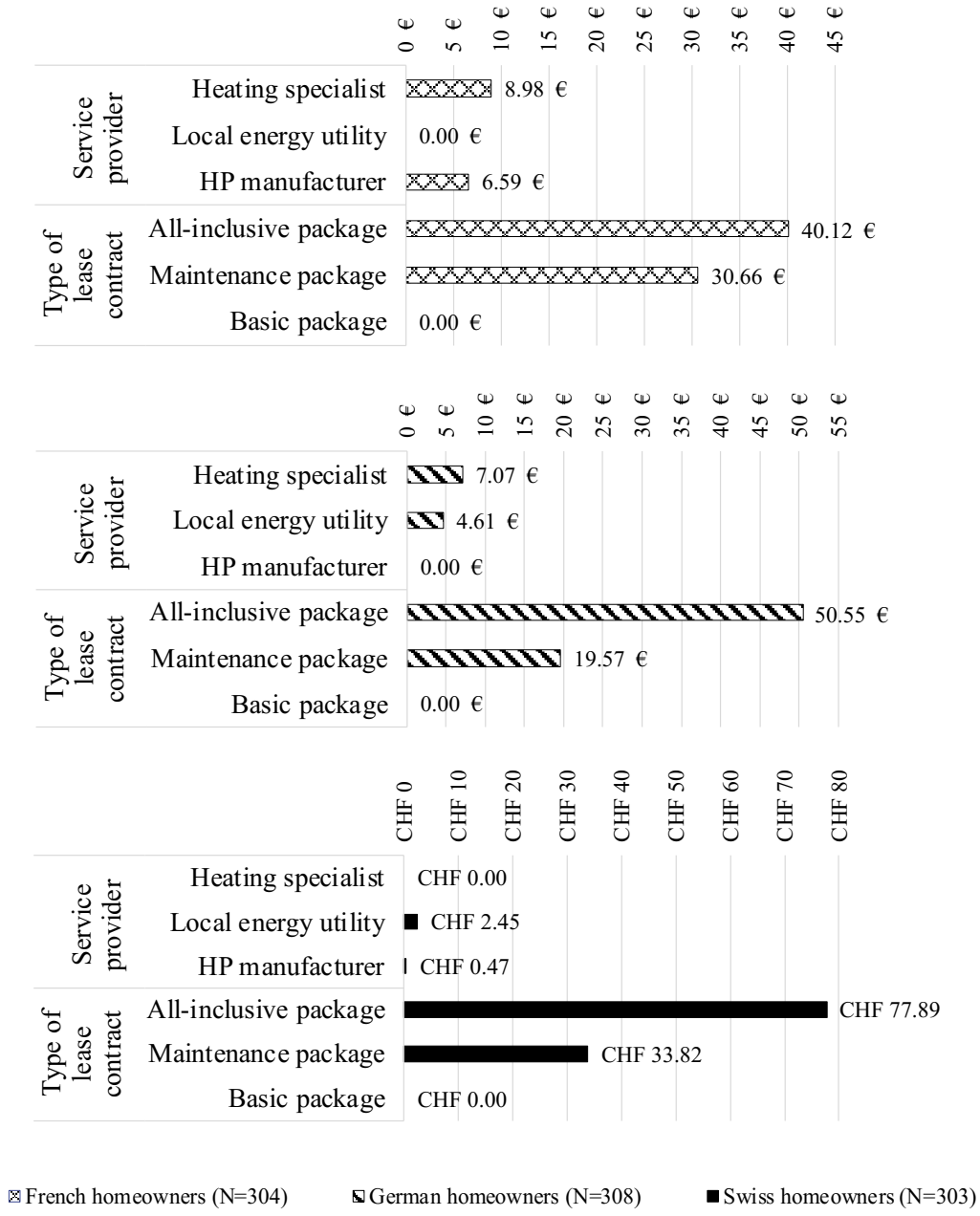


Figure 4: Monthly willingness to pay of homeowners for heat-pump leasing services.

Moreover, French homeowners would be willing to pay up to 30.66 € per month to move from a basic package that comprises a heat pump and installation to one that also includes yearly maintenance, whereas Swiss homeowners would pay up to 33.82 CHF monthly. In contrast, German homeowners would only pay up to 19.57 € per month. Despite operation and maintenance being an important concern for German homeowners, these respondents seem to view the risk of encountering complications during such activities to be relatively low compared to French homeowners. As for all-inclusive packages, preferences appear to be similar across countries. While French

homeowners would be willing to pay up to 40.12 € per month for an all-inclusive package that in addition to basic features would include yearly maintenance and potential repair activities, German homeowners would be willing to pay up to 50.55 € monthly. Interestingly, the difference between the WTP of German homeowners for an all-inclusive package and maintenance package (30.98 €) is considerably higher than that of French homeowners (9.46 €). These findings show that German homeowners tend to differentiate more than their French counterparts between all-inclusive and maintenance packages. They also suggest that German homeowners may be willing to pay more than three times as much as their French counterparts for subscription-based repair services, or to shield themselves against the risk of a technical failure. Similarly, Swiss homeowners would also pay considerably more for an all-inclusive package than for a maintenance package (up to 44.07 CHF per month). Overall, these findings stress the relevance of providing heat pump services, especially in Germany where the degree of diffusion is low and interest in leasing high (see Subsection 3.3).

4. Conclusions and policy implications

This study has investigated the preferences of homeowners for heat-pump leasing, examined their inclination to lease or purchase such a system, and quantified their willingness to pay for different heating services. It has also clarified the drivers and barriers of heat-pump adoption and leasing. Achieving net-zero carbon emissions will require considerable investment in residential heat pumps, and asset leasing could contribute to addressing some of the barriers to diffusion. Based on 9,150 experimental leasing decisions made by 915 single-family homeowners in France, Germany, and Switzerland, we provide novel empirical insights about preferences related to heat-pump adoption across different countries. We also draw conclusions for the design of lease offerings and related policy measures.

We show that heat pumps have the potential to become a dominant technology in the three countries. Overall, adoption is mainly driven by the ambition to curb environmental impact and avoid dependence on foreign energy sources. A desire to hedge against energy price increases also emerged as a main driver for German and Swiss homeowners, who tend to be more reliant on fossil fuels for heating. In contrast, homeowners also view policy incentives as being an important driver of heat-pump diffusion in France, which has emerged as the leading European market in terms of unit

sales. However, financial and technical factors appear to challenge heat-pump diffusion across these three countries.

Our results indicate that heat-pump leasing could address some of these barriers by removing the need for an initial lump-sum investment to purchase the equipment, and simplifying maintenance and repair activities. Monthly lease payments and the type of lease contract emerged as the most important considerations in leasing decisions. Homeowners prefer leasing offerings with lower monthly payments in which the heat pump, installation, yearly maintenance, and all potential repair activities are included. Their average willingness to pay for an all-inclusive package relative to a basic package that would only include the heat pump and installation is similar across countries. However, German homeowners would on average pay up to three times as much as their French counterparts for an all-inclusive package than for a maintenance package in which only the heat pump, installation, and yearly maintenance are included (up to 30.98 € and 9.46 € per month, respectively). Similarly, Swiss homeowners would also be willing to pay considerably more for subscription-based repair services (up to 44.07 CHF per month). These findings show that German and Swiss homeowners tend to differentiate more than their French counterparts between all-inclusive and maintenance packages. They also point to an apparent reluctance of these homeowners to take on any technical risk. The service provider was found to play only a secondary role in leasing decisions. While homeowners appear to be somewhat keener to lease a heat pump from a heating specialist or local energy utility, diversifying the types of providers could be a desirable way to meet the preferences of a wider range of end-users.

Moreover, we show that most homeowners have strong preferences for either leasing or purchasing. Swiss homeowners who plan to install a heat pump are those least likely to lease: only 19.8% of respondents expressed a strong preference for leasing as opposed to 55.9% who strictly chose purchasing. This may be explained by their greater affluence and the relatively high degree of heat-pump diffusion in the country. In contrast, 44.7% of German homeowners revealed a strong preference for leasing and 24.5% for purchasing, whereas only 33.9% of French homeowners chose leasing while 40.3% chose purchasing. Therefore, German homeowners appear to be those most likely to leasing a heat pump. This can be explained by the fact that heat pumps are relatively less common in Germany, and that homeowners may tend to view the risk of technical failure as high. Hence, our findings highlight the relevance of asset leasing, especially in markets in which heat pumps are at an early stage of diffusion. However, our results

also show that the length of leasing agreements is perceived as a major drawback, underlining the relevance of offering flexible contracts.

Further, despite a general trend towards low-carbon heating adoption, our results indicate that a considerable share of homeowners would be likely to choose to replace their main heating systems with natural-gas-fired or heating-oil boilers if they were allowed to do so. This is especially so in the case of Germany, where fossil fuels contribute to heating the great majority of homeowners' single-family houses. Although, this preference for fossil-fuel heating may have changed since the beginning of the Russo-Ukrainian war in Europe.

Building on these insights, we specify four implications for service providers and policy makers. First, heating specialists, local energy utilities, and heat pump manufacturers could consider providing – alone or in collaboration – lease offerings in which the heat pump, installation, yearly maintenance, and potential repairs and part replacement costs are all included. Since uncertainty about operational performance appears to be an important barrier to heat-pump adoption for German homeowners, service providers could also consider offering a performance guarantee (i.e., efficient asset leasing). For example, they could reimburse, fully or partly, the cost of the electricity used to operate the heat pump. This type of service-based business model may be particularly relevant for markets at an early stage of diffusion. Second, since the length of leasing agreements appears to be a drawback, service providers could put forward the option for homeowners to terminate leasing contracts at any time by paying the remainder of what is owed for the heat pump and installation (lease-to-own). Third, policy makers who wish to promote the adoption of heat pumps could consider providing support tailored to different modes of adoption, including asset leasing. For example, this could be achieved by reforming income tax regimes so that monthly lease payments can – at least partly – be deducted for tax purposes, as suggested by Schleich et al. (2021). Fourth, since a considerable share of homeowners plan to install natural-gas-fired or heating-oil-fired boilers in their houses beyond 2025, policy makers may wish to consider strengthening country-wide energy efficiency or carbon emission regulations to ensure the timely phaseout of fossil-fuel heating in residential buildings. This could set countries on the path of meeting their climate goals whilst reducing their dependence on fossil fuel imports.

The limitations of this study indicate avenues for future research. First, we applied a stated-preference method to investigate the preferences of homeowners for heat-pump leasing offerings. This strategy is pertinent, given the novelty of these services and the

scarcity of the historical data required to implement revealed-preference methods. However, not all respondents will transpose their intentions into actual leasing decisions. As service-based offerings expand into markets, scholars could further examine preferences for heat-pump leasing in different countries using revealed-preference methods. Second, this study focused on owners of single-family houses, as heat-pump diffusion has historically been greater for these buildings than for multi-family buildings. Research could also explore the role of service-based business models in decarbonizing other types of buildings (e.g., multi-family residential, business, or industrial buildings). Third, while this study focused on asset leasing, scholars could also explore preferences for other types of service-based offerings such as heat as a service – i.e., a business model whereby financial, technical, performance, behavioural, and energy price risks are all borne by service providers (Delta-EE, 2019). Fourth, as we propose tailoring policy measures to account for service-based offerings, scholars could elaborate on what types of policy incentives are preferred by end-users and industry actors. Finally, the results of this study are drawn from datasets from three specific countries. Further research could also look at how preferences for service-based offerings differ in other markets.

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Disclaimer

The results and conclusions in this publication reflect only the author’s view. The European Commission and Romande Energie SA are not responsible for any use that may be made of the information it contains.

Appendix

Table A.1: Socioeconomic and demographic descriptive statistics.[a, b]

Variable name	Description	% in French subsample (N=304)	% in French population	Description	% in German subsample (N=308)	% in German population	Description	% in Swiss subsample (N=303)	% in Swiss population
Region[c]	Ile de France	12.5%	18.9%	South	29.9%	29.2%	German-speaking	74.6%	62.6%
	Northwest	24.3%	20.0%	North	19.2%	16.2%	French-speaking	25.4%	22.9%
	Northeast	20.1%	22.0%	West	33.1%	35.2%	Italian-speaking		8.2%
	Southwest	25.3%	18.4%	East	17.9%	19.4%	Romansh-speaking		0.5%
	Southeast	17.8%	20.7%						
Sex	Male	49.0%	47.6%	Male	47.4%	48.9%	Male	57.1%	49.2%
	Female	51.0%	52.4%	Female	52.6%	51.1%	Female	42.9%	50.8%
Household income[d]	*Monthly net income*			*Monthly net income*			*Monthly gross income*		
	Up to 1,499 €	9.2%	22.2%	Up to 1,499 €	9.1%	23.1%	Up to 6,000 CHF	14.2%	30.0%
	1,500–2,499 €	38.2%	48.7%	1,500–3,499 €	49.0%	48.2%	6,001–9,000 CHF	22.1%	25.0%
	≥ 2,500 €	52.6%	29.2%	≥ 3,500 €	41.9%	28.1%	9,001–12,000 CHF	26.4%	19.0%
							> 12,000 CHF	37.3%	27.0%
Age	18–29 years	5.9%	25.0%	18–29 years	7.8%	16.0%	18–29 years	4.3%	17.4%
	30–44 years	24.7%	15.7%	30–44 years	18.5%	30.2%	30–44 years	20.5%	26.0%
	45–59 years	26.6%	33.0%	45–59 years	29.9%	19.2%	45–59 years	38.3%	26.8%
	≥ 60 years	42.8%	26.3%	≥ 60 years	43.8%	34.7%	≥ 60 years	37.0%	29.8%
Level of education[e]	Low /middle	52.3%	68.3%	Low /middle	63.6%	66.4%	Low /middle	65.0%	62.0%
	High	47.7%	32.4%	High	36.4%	33.6%	High	35.0%	38.0%
Level of wealth[f]	Yes	25.0%	n.a.	Yes	40.3%	n.a.	Yes	71.3%	n.a.
	No	70.4%	n.a.	No	50.0%	n.a.	No	25.7%	n.a.
	Rather not say	4.6%	n.a.	Rather not say	9.7%	n.a.	Rather not say	3.0%	n.a.

* Notes can be found on the next page.

Table A.1 – additional notes:

[a]Aggregated percentages could differ from 100% due to potential rounding errors.

[b] National population statistics are drawn from the French National Institute of Statistics and Economic Studies (*Institut national de la statistique et des études économiques, Insee*), French National Institute of Demographic Studies (*Institut national d'études démographiques, Ined*), German Federal Statistical Office (*Statistisches Bundesamt, Destatis*), Swiss Federal Statistical Office (*Office fédéral de la statistique, OFS*), Statista and Eurozensus.

[c] *Regions*: French Northwest (incl. Brittany, Centre-Val de Loire, Normandy, and Pays de la Loire), Northeast (Bourgogne-Franche-Comté, Grand Est, Hauts-de France), Southwest (New Aquitaine, Occitania), and Southeast (Auvergne-Rhône-Alpes, Corse, Provence-Alpes-Côte d'Azur); German South (incl. Bavaria and Baden Württemberg), North (Hamburg, Bremen, Schleswig-Holstein, Lower Saxony), West (Saarland, Hesse, North Rhine-Westphalia, Rhineland-Palatinate), and East (Berlin, Brandenburg, Thuringia, Saxony, Saxony-Anhalt, Mecklenburg-Western Pomerania); Swiss German-speaking (incl. all economic zones contained in the Alps and Pre-Alps, West Midland, and East Midland regions as defined by the WEMF / REMP) and French-speaking (incl. all economic zones contained in the Swiss Romandie region).

[d] *Household income*: monthly net income values were used in the French and German survey, whereas monthly gross income was used in the Swiss survey to reflect country-specific practices.

[e] *Levels of education*: French low and middle education levels (incl. respondents with no diploma or certificate of education, *Brevet des collèges*, CAP, BEP, Bac, *brevet professionnel*) and French high education level (Bac + 2 or higher diploma); German low and middle education level (incl. respondents with no diploma, secondary (elementary) school-leaving certificate, and *Realschule* or equivalent qualification), German high education level (advanced technical college qualification or general university qualification); Swiss low and middle education levels (incl. respondents with no school-leaving qualification, compulsory school, household apprenticeship, commercial school, apprenticeship, diploma school, technical college, traffic school, vocational apprenticeship, full-time vocational school) and Swiss high education level (Matura, vocational baccalaureate, teacher training college, university, ETH, FH, PH, and higher vocational training).

[f] *Level of wealth*: the ability to invest 30,000 € (or 50,000 CHF) without a loan from a bank, an acquaintance or a relative.

Table A.2: Descriptive statistics.

Variable name	Description	% in French subsample (N=304)	% in German subsample (N=308)	% in Swiss subsample (N=303)
Construction period	*Period of construction of the single-family house.*			
	Before 1946	21.4%	20.5%	17.5%
	1946–1980	28.3%	37.7%	24.1%
	1981–2000	27.0%	25.6%	32.0%
	2001–2020	21.7%	15.6%	25.1%
	After 2020	1.6%	0.6%	1.3%
Living space	*Living space of the single-family house.*			
	Up to 119 square meters	59.9%	21.8%	9.9%
	120–159 square meters	30.9%	45.8%	52.1%
	160 square meters or more	9.2%	32.5%	38.0%
Operating duration	*Operating duration of the main heating system.*			
	Up to 5 years	24.0%	23.7%	17.8%
	6–15 years	35.2%	29.5%	35.6%
	16–25 years	20.7%	23.7%	27.7%
	More than 25 years	17.4%	21.1%	17.2%
	I don't know	2.6%	1.9%	1.7%
Retrofit plans	*Planning to replace the main heating system within the next 5 years.*			
	Yes	25.0%	25.3%	23.1%
	No	62.2%	65.3%	70.3%
	I don't know	12.8%	9.4%	6.6%
House acquisition	*Since when the single-family house has been owned by respondent.*			
	Before 1980	3.6%	8.8%	4.6%
	1980–1989	12.5%	14.3%	11.9%
	1990–1999	12.5%	17.2%	22.4%
	2000–2009	23.0%	22.4%	30.0%
	After 2010	44.7%	32.8%	30.4%
	Don't know	3.6%	4.5%	0.7%
Residency status	*Residing primarily in the single-family house (primary residence).*			
	Yes	96.4%	96.1%	93.7%
	No	3.6%	3.9%	6.3%
Residential buildings owned	*Total number of residential buildings owned.*			
	1–2	96.4%	95.8%	90.8%
	3–5	3.3%	4.2%	7.6%
	More than 5	0.3%	0.0%	1.7%
Heating Cost	*Estimated average annual heating-related costs (in € / CHF).*	1,336 € (N=247)	1,859 € (N=247)	2,104 CHF (N=214)

Table A.3: Robustness checks – Mean utility estimates by attribute level, expressed as difference to the baseline level for all homeowners within national subsamples.

			HB models			*P*-value for Mann Whitney *U* test (2-tailed)[a]		
			French HB model (1)	**German HB model (2)**	**Swiss HB model (3)**	Difference test between **(1) and (2)**	Difference test between **(1) and (3)**	Difference test between **(2) and (3)**
Subsample size (N)			304	308	303			
Number choice sets			3040	3080	3030			
Attribute	**Attribute level**							
Monthly lease payment	130 € (or 195 CHF)	*(Baseline)*	0	0	0			
	155 € (or 230 CHF)		–41.61	–46.08	–42.45	0.509	0.911	0.441
	180 € (or 265 CHF)		–113.61	–108.30	–90.19	0.312	0.000 ***	0.008 ***
Type of lease contract	Basic package	*(Baseline)*	0	0	0			
	Maintenance package		69.67	42.39	43.58	0.000 ***	0.000 ***	0.827
	All–inclusive package		91.15	109.49	100.35	0.001 ***	0.036 **	0.181
Service provider	Heat pump manufacturer	*(Baseline)*	0	0	0			
	Local utility		–14.99	9.98	2.56	0.000 ***	0.001 ***	0.081 *
	Heating specialist		5.42	15.31	–0.60	0.004 **	0.128	0.000 ***

[a] *** Significance level of 1% ($p < 0.01$), ** Significance level of 5% ($p < 0.05$), * Significance level of 10% ($p < 0.1$).

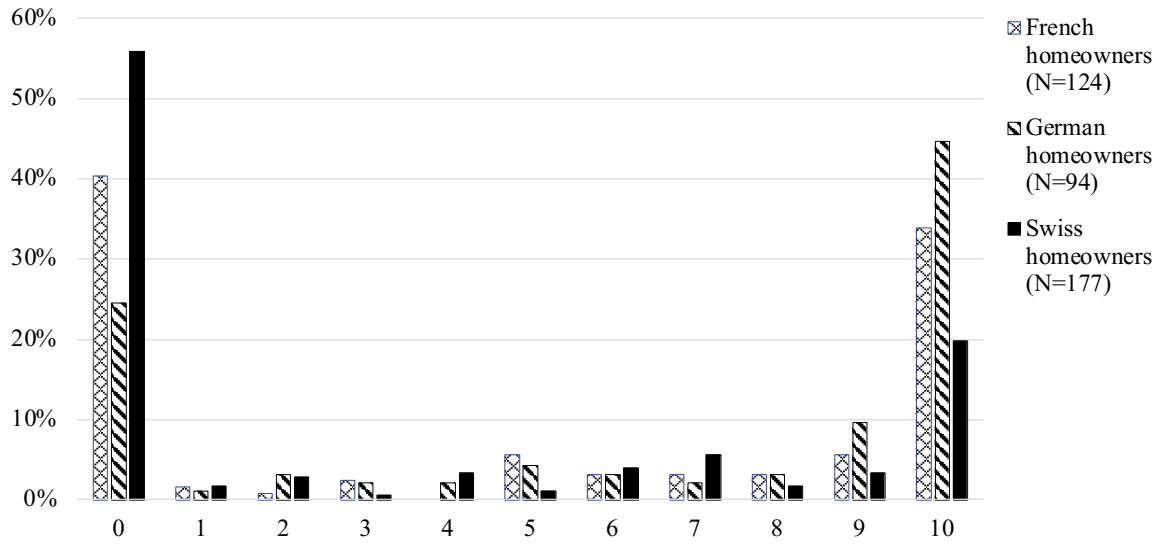


Figure A.1: Share of homeowners who planned to replace their heating system with a heat pump by the number of times they chose to lease the heat pump instead of purchasing it in all DCE choice tasks.

Table A.4: Robustness checks – Mean utility estimates by attribute level, expressed as difference to the baseline level for homeowners who passed all manipulation checks and who planned to install a heat pump.

	HB models			P-value[a]			
	All country-specific homeowners (1)	**Passed all manipulation checks (2)**	**Planned to install heat pump (3)**	Difference test between **(1) and (2)**		Difference test between **(1) and (3)**	
France							
Model size (N)	304	82	124				
Share of subsample	100.0%	27.0%	40.8%				
Attribute level							
130 € (195 CHF) *(Baseline)*	0	0	0				
155 € (230 CHF)	–41.61	–36	–38	0.444		0.362	
180 € (265 CHF)	–113.61	–110.55	–104.68	0.700		0.198	
Basic package *(Baseline)*	0	0	0				
Maintenance package	69.67	69.11	77.8	0.765		0.174	
All–inclusive package	91.15	97.15	99.48	0.451		0.134	
Manufacturer *(Baseline)*	0	0	0				
Local utility	–14.99	–14.94	–35.48	0.680		0.001	***
Heating specialist	5.42	10.93	–5.60	0.768		0.180	
Germany							
Model size (N)	308	102	94				
Share of subsample	100.0%	33.1%	30.5%				
Attribute level							
130 € (195 CHF) *(Baseline)*	0	0	0				
155 € (230 CHF)	–46.08	–52.17	–46.66	0.309		0.748	
180 € (265 CHF)	–108.30	–122.68	–109.65	0.099	*	0.835	
Basic package *(Baseline)*	0	0	0				
Maintenance package	42.39	38.93	45.12	0.465		0.969	
All–inclusive package	109.49	103.65	104.61	0.395		0.749	
Manufacturer *(Baseline)*	0	0	0				
Local utility	9.98	8.96	7.95	0.762		0.606	
Heating specialist	15.31	15.58	13.04	0.654		0.667	
Switzerland							
Model size (N)	303	105	177				
Share of subsample	100.0%	34.7%	58.4%				
Attribute level							
130 € (195 CHF) *(Baseline)*	0	0	0				
155 € (230 CHF)	–42.45	–46.43	–44.82	0.447		0.855	
180 € (265 CHF)	–90.19	–95.08	–100.41	0.732		0.234	
Basic package *(Baseline)*	0	0	0				
Maintenance package	43.58	56.3	44.93	0.030	**	0.677	
All–inclusive package	100.35	107.47	97.14	0.220		0.628	
Manufacturer *(Baseline)*	0	0	0				
Local utility	2.56	–15.75	–10.68	0.030	**	0.036	**
Heating specialist	–0.60	–6.15	–10.49	0.781		0.053	*

[a] *** Mann Whitney *U* test (2-tailed): significance level of 1% ($p < 0.01$), ** Significance level of 5% ($p < 0.05$), * Significance level of 10% ($p < 0.1$).

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