Accepted author manuscript
August 22, 2021 – Journal of Cleaner Production

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Mobilising mainstream finance for a future clean energy transition: The case of Finland

Abstract
Financing the clean energy transition is a growing field of research, yet most research on investments in clean energy has focused on the early stage, and hence on the role of public policy and private equity such as venture capital. We examine how the clean energy sector enters the stage of mainstream financing, using Finland as an empirical case. We combine data from expert interviews and secondary sources, which are analysed using the Technological Innovation Systems framework to identify the enablers and barriers of the TIS functions of the market motor. The findings show the interdependency of the various TISs of the clean energy sector especially in creating a stable market for the developing technologies. Especially the growth of investments in renewable power production is dependent on the growth of investments in electrification and the management of intermittency of power production.

Keywords
Finance
Energy transition
Technological Innovation Systems
Market formation
Resource mobilisation

1 Introduction
Financing the clean energy transition is a growing field of research, yet most research on investments in clean energy has focused on the early stage, and hence on the role of public policy and private equity such as venture capital (e.g. Bürer and Wüstenhagen, 2009; Polzin et al., 2019). However, renewable energy has become competitive vis-à-vis new fossil fuel production in large parts of the world (IRENA, 2019). Therefore, studying mainstream financing (e.g. Karltorp et al., 2017, Polzin and Sanders, 2020) has gained increasing interest.

Even if the absolute investment gap might be smaller than expected (Polzin and Sanders, 2020, Polzin et al., 2021), reviews still show numerous barriers on the way to the transition (e.g. Hafner et al. 2019, 2020). Commonly reported barriers include technological risks, policy dependence and capital intensity of technologies as well as complexity of administrative processes, public resistance, and path dependency.

Moreover, significant competence build-up in the financial sector is needed, including a turn away from short-termism.

The systemic nature of the transition has been shown to affect the financing (e.g. Hafner et al., 2020). However, no simultaneous analysis has been carried out of the barriers to investments in energy production, electrification of the energy system and storages as means of managing the intermittency of energy production.

Karltorp (2016) described two valleys of death for mobilising resources for developing technologies. We focus on the second valley of death where technology moves from early commercialisation to full commercialisation and large-scale diffusion. Building on Karltorp's work, we define mobilising mainstream finance as a challenge in the second valley of death, when finance needs to be raised from banks and institutional investors who tolerate less risk than venture capitalists. In this study, we consider as investors project developers (e.g. energy companies, other project developer companies, energy users) who invest their own equity in projects, external providers of loans and equity (e.g. banks, funds, institutional investors) and external guarantors which influence the cost of capital (e.g. public development banks, power-purchase agreement customers), but exclude venture capital. We ask how the various enablers of and barriers to investments in renewable energy production, electrification and storage interact in the second valley of death (Karltorp, 2016).

As our analytical framework, we use Technological Innovation Systems (TIS), which illustrates the progress of a technological innovation through seven interlinked functions (e.g. Hekkert et al., 2007; Andersson et al., 2021). One of the functions is resource mobilisation. While financial capital is regularly mentioned in such analyses (e.g. Quitzow, 2015; Mäkitie et al., 2018), private finance has rarely gained a central role in the TIS literature thus far (Bergek, 2019), and understanding on how resource mobilisation links to other functions of TIS is still limited. Therefore, our research contributes to prior TIS analyses by focusing on the mobilisation of financial resources (Karltorp, 2016; Karltorp et al., 2017; Polzin et al., 2016) and exploring the case of a developed country in its efforts to pass the second valley of death.

Most TIS studies focus on individual technologies (Quitzow, 2015) or make comparisons of a few technologies (Karltorp, 2016). However, intermittent power production will change the structure of the entire energy system. Therefore, our starting point is that a stable market for renewable power production requires investments in technologies managing the intermittency of the production, such as transmission, storages and power-to-X-technologies, as well as in energy efficiency (WEC, 2019) and electrification of industry, heating and mobility (Pursiheimo et al. 2019). The interaction of the various energy TISs has been recognised (Bergek et al., 2015; Mäkitie et al., 2018) and further research on this aspect has been called for (Markard et al., 2015). Therefore, our main objective is to find out how the enabling and hindering of the relevant TIS functions of energy production, electrification and storages interact at the stage of market formation of TISs, i.e. the full commercialisation of the technologies.

The remainder of the paper is organised as follows. In the following section, we position our research in relation to the relevant literature on clean energy investment and TIS. The methodology section describes the research data and the context of the study. The findings present the enablers of and the barriers to the TIS functions contributing towards investments. We then discuss the novelty of the results and our contribution to the TIS literature and show the interdependency in the mobilisation of resources into the various TISs of the clean energy sector. Finally, we conclude and present policy implications.

2 Literature review

In the following, we focus on research exploring the consequences of the cost decline in renewable energy, the treatment of resource mobilisation in the TIS literature, as well as literature addressing the interconnectedness of different technologies within an emerging clean energy sector.

2.1 Financial resource mobilisation for clean energy investment as markets evolve

The literature on clean energy investment is rapidly evolving. Assessments have been made of how much investment is needed globally to keep global warming within a 1.5°C target (Hafner et al., 2020; Polzin et al., 2019), but it has also been argued that these need to be linked to investment streams (Polzin et al., 2021). This is all the more the case now that renewable energy has grown out of a narrow niche, and is entering the mainstream, thanks to cost declines resulting from technological learning (Polzin et al. 2021). On a global scale, the cost driver is further supported by climate policies and the ensuing increasing demand for clean energy infrastructure, as well as activist investor groups, emerging business models (Bass and Grøgaard 2021) and emerging internal capabilities in multinational enterprises (Patala et al. 2021). While there are powerful drivers, clean energy technology investment has been hampered by barriers, such as technological risks in the deployment of novel technologies, the policy dependence and related uncertainties of renewable energy investments (e.g. Jacobsson and Jacobsson, 2012; Andersson et al., 2021), and the capital intensity of technologies like wind and solar power (Hafner et al., 2019; Polzin et al., 2019). Some barriers such as investment professionals' scepticism (Campiglio et al., 2017; Christophers, 2019) might be easing, even though clean energy investment still requires significant competence build-up in the financial sector (Polzin and Sanders 2020), as well as a relaxing of liquidity requirements on institutional investors in order to reach the necessary scale (Polzin et al. 2021). Other barriers, such as the complexity of administrative processes, public resistance and path dependency (Hafner et al., 2020), may remain or change form as the clean energy sector evolves.

As the market has evolved, the emphasis is shifting from research on venture capital and equity investment to include debt (Ng 2018; Xie et al. 2021), and from policy to market-led developments and the necessary reforms to private finance regulations (Polzin and Sanders 2020; Polzin et al. 2021). Recent research has also turned to investigating the conditions for large-scale deployment of renewables such as wind and solar power as they have reached maturity. Here, technologies like wind power face what is called the second valley of death, which occurs between early commercialisation and large-scale rollout of the technology in the mainstream market (Geddes and Schmidt 2020; Karltorp et al. 2017). This requires substantial capital in proportion to the developers' own balance sheets (Karltorp, 2016; Karltorp et al., 2017), and a capacity to carry the risks of large-scale infrastructure projects (Mazzucato and Semieniuk 2018; Semieniuk et al., 2021).

Capital, within the capital requirements of commercial banks, is abundant in regions like Europe and the USA, which have experienced significant financial easing by central banks (Arezki et al., 2017; Campiglio et al., 2018). For example, in Europe, Polzin and Sanders (2020) find that there are sufficient finance options available to fill the clean energy investment gap – keeping in mind that investment in clean energy implies investing in a portfolio of projects including both mainstream and emerging technologies as well as divestment from declining technologies (Polzin et al. 2021; Hoang et al. 2021). If we accept the argument that under current conditions, capital is generated when creditworthy and profitable projects are developed and "sold" to finance providers (Campiglio et al., 2017), resource mobilisation by clean energy project developers becomes a relevant perspective to examining the drivers of clean energy investment. Resource mobilisation is one of the seven interlinked functions that have been extensively studied by the technological innovation systems (TIS) framework as necessary conditions for the success of innovative new technologies. In this framework, resource mobilisation is closely linked to six other functions: knowledge development and diffusion, entrepreneurial activities, guidance of the search, market formation, legitimation and development of positive externalities (Jacobsson and Bergek, 2011; Suurs 2009).

2.2. Technological innovation systems and the mobilisation of financial resources

A technological innovation system is a "set of actors, networks, institutions and technology engaged in developing, diffusing and utilising new products (goods and services) related to a certain technological field or industry" (Mäkitie et al., 2018, p. 814; Jacobsson and Bergek, 2011). This perspective has been widely applied to analysing the enablers and barriers in the progress of systems (Jacobsson and Bergek, 2004, 2011; Bergek et al., 2008). Indeed, recent TIS literature has started to explore the mobilisation of financial resources, acknowledging that it presents different problems at each stage of maturity (Polzin et al., 2016): nascent technologies need to mobilise public support such as RDI and feed-in-tariffs (Polzin et al., 2019), whereas emerging technologies need to mobilise equity investments, for example venture capital (Karltorp, 2016).

TIS analyses conceptualise the mobilisation of resources as an exchange between two different sectors (finance and energy) that operate under different logics. For example, Karltorp (2016) examined challenges in mobilising financial resources for biomass gasification and offshore wind power, highlighting *the lack of alignment between the project developers' and the financial sector's logics* as a key challenge, in particular in terms of a lack of knowledge and business models allowing for an alignment of these communities' different logics (see also Polzin et al., 2016; Polzin and Sanders, 2020). Moreover, the links between functions have been shown to be necessary in commercialisation and investments (Karltorp, 2016; Andersson et al., 2021). In a similar vein, Geddes and Schmidt (2020) examined how state investment banks serve to educate both the private financial sector and clean energy developers by for example developing standards, codified knowledge, tools and processes that facilitate the interaction between private investors and clean energy project developers.

TIS analysis is based on understanding both the structural elements and the functions of the system (Hekkert et al., 2007; Bergek et al., 2008), which together explain how the system evolves. The interdependency of the functions has been conceptualised in terms of "motors of innovation" (Suurs, 2009; Suurs and Hekkert, 2009). A technological innovation system navigates through the second valley of death and becomes self-sustaining once a "market motor" has emerged to replace the previous "system-building motor" based on policy intervention and advocacy coalitions. The market motor emerges through cumulative causation, where system-building (especially the creation of demand) leads to entrepreneurial activities, i.e., entrepreneurs perceiving a demand and entering the market and mobilising investment, This in turn increases expectations (guidance of the search) and subsequently attracts even more companies (entrepreneurial activity) and investment (resource mobilisation) (Suurs and Hekkert, 2009). At this stage, companies take over market formation from policy makers, and integrate it into their normal marketing and promotion work to create a stable market either domestically or internationally (van der Loos et al., 2020). However, the knowledge development and diffusion function remains important, since it enables learning and hence increasing returns (Jacobsson et al., 2017). Once this stage is reached, the TIS is internally resourced through stable market demand (Walrave and Raven, 2016), thus motivating the necessary investments. The problematic of the second valley of death is how to create such a "market motor" (Figure 1).

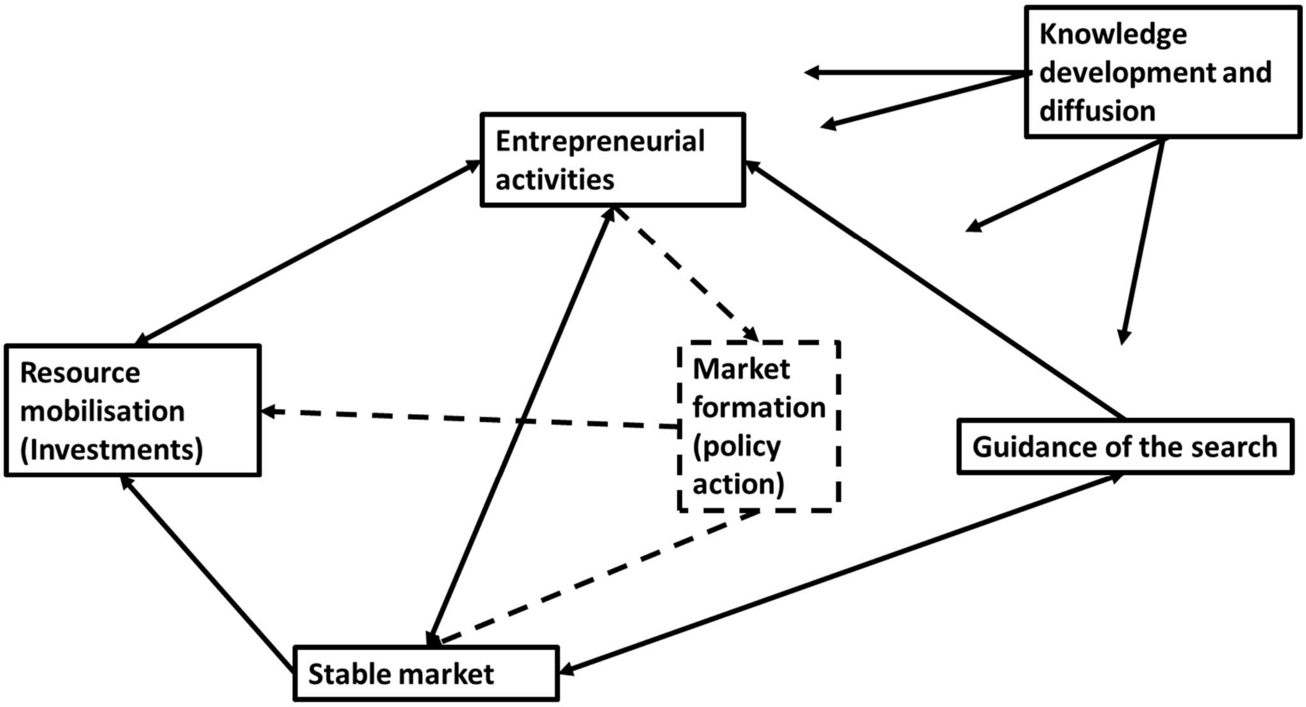

Figure 1. The market motor (solid lines) and some features of the system building motor of a TIS (dashed lines) (modified from Suurs, 2009).

2.3 Investigating interrelations between TISs within the clean energy sector

Market demand for clean energy exhibits a second pattern of cumulative causation, which extends outside individual TISs. Most commentators argue that a sustainable clean energy sector builds primarily on wind and solar power expansion and removes fossil fuels entirely from the energy mix (Bogdanov et al., 2019; Pursiheimo et al., 2019). This requires a significant degree of electrification of industry, transport and heating end-uses (Pursiheimo et al., 2019). A shift to intermittent power sources also requires significant investment in energy storage (Bogdanov et al., 2019; Hoang and Nugyen, 2021) to balance electricity demand and supply. There is also a financial angle to the intermittency of power production. Since wind and solar power have zero marginal cost, they are expected to drive down electricity market prices and increase price variability (Frei et al., 2018; Wozabal et al., 2016). Hence, electrification, demand response and storage become critical for the profitability of power production investments (Polzin and Sanders, 2020). Indeed, one can argue that the interconnections between clean electricity production, use and storage are central for the development of a “market motor” not only for the entire sector, but also for each of the different technologies involved. This is complicated by the fact that different technologies within the sector exhibit different degrees of maturity, and hence, face different problems of finance (Polzin and Sanders, 2020; Polzin et al. 2021).

Existing TIS analyses focusing on financial resource mobilisation for clean energy emphasise the need for a close analysis of the degree of alignment between project developers and finance providers, by technology type and maturity (Karltorp, 2016; Polzin et al., 2016; Polzin and Sanders 2020). This is particularly important when addressing clean energy technology in its entirety, consisting of several technologies at different stages of maturity and attracting diverse investors, for example for large scale infrastructure-type projects like offshore wind, compared to user-driven and venture investments required for electrification (Polzin and Sanders 2020). Hence, the profiles of investors in relatively mature and large-scale technologies are likely to differ from those investing in small, distributed assets required for electrification of end-uses (Polzin et al. 2021). Energy users investing in clean energy apply an entirely different logic from that of purely energy producers: instead of making a profit, investments often serve to secure energy for one's own use (Heiskanen et al., 2017b; Salm et al., 2016), while they also face barriers due to the lack of standard evaluation criteria for projects (Polzin et al. 2021). Given these varying logics, it is likely that knowledge development and diffusion are required beyond the individual TISs (see Geddes and Schmidt 2020), in order to influence the guidance of the search across the separate TISs within the sector towards a view of a future, electrified clean energy sector.

The TIS perspective has been criticised for focusing on individual technologies rather than taking into account the sectors in which they develop, other technologies or context factors (Markard et al., 2015; Bergek et al., 2015). This is not, however, a limitation of the framework itself but a choice made by analysts and can vary widely depending on the technological field and research question (Markard et al., 2015). Bergek et al. (2015, p. 56) state that a TIS can even "be so integrated to the sector that it might not even be interesting to analyse it as a separate TIS". Indeed, TIS analyses have highlighted the interaction of financial resource mobilisation with factors external to the focal TIS, such as developments in parallel TISs, the entire energy sector, and in the financial sector (Karltorp et al., 2017). However, investment needs in the clean energy sector are usually addressed one technology at a time, as if this interdependency did not exist (e.g., IPCC 2018). In this paper, we attempt to breach this research gap by investigating the interdependency in the mobilisation of resources into the various TISs that make up the clean energy sector.

3 Methodology

Our paper is based on an empirical examination of the investment logics of various actors in relation to the development of power production and transmission, electrification of heating and transport as well as the nascent technologies of power storage, demand response and power-to-X (referring to various technologies where cheap electricity is used to produce hydrogen from water; hydrogen can be stored and later used for various purposes). We chose to use the TIS framework for our analysis, because it is well suited for gaining qualitative understanding of the development towards full commercialisation (Andersson et al. 2021) and increasingly used for the analysis of the logics of investments in novel technologies. It is not intended to produce quantitative data on investments.

We analysed several TISs within the clean energy sector in order to capture their interdependencies caused by the shared markets and knowledge base (Figure 2). In particular, we pay attention to the co-evolution of clean power production technologies and technologies that enable electrification and storage, with a focus on the alignment between the logics of finance providers and project developers, and the dependence of resource mobilisation on other functions, potentially cutting across several TISs, such as knowledge development and diffusion, entrepreneurial activities and guidance of the search.

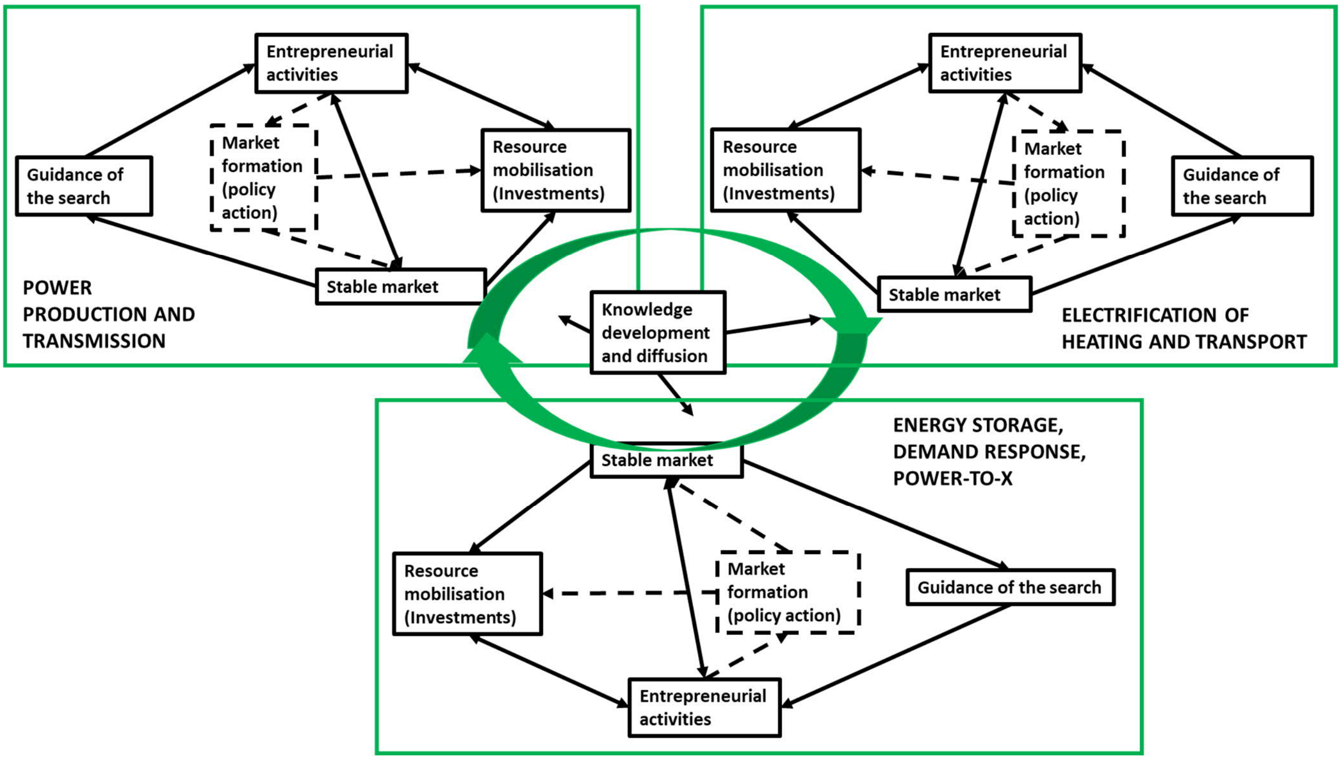

Figure 2. Analytical framework for the TIS analysis of enablers of and barriers to investments in selected TISs of the clean energy sector.

3.1 Research data

We combine bottom-up data from several sources: a scenario analysis of new capacity required for a fossil fuel free energy system (Rinne et al., 2019), as well as a broad desktop study including industry data on current investment levels, branch reports, company literature, as well as other statistical and secondary sources (Appendix B). In addition, we interviewed 16 experts on energy investments, including investors, project developers and researchers (Table 1).

Table 1. Interviews

Organisation	Position	Type of organisation
S-pankki	investment director	Mainstream bank
Keva	head of responsible investment	Pension fund
Taaleri Energy	investment director	Investment bank
Nordic Investment Bank	lending manager; communications director	Public credit institution
Nordic Development Fund	programme manager	Development finance institution
MuniFin	lending manager	Public credit institution
Finnish Climate Fund	managing director	State-owned special assignment company
Wind Power Association	managing director	Renewable energy lobby
Energy Industries	managing director	Energy industry lobby
Fingrid	finance director; treasurer	Transmission System Operator (TSO)
St1	renewable energy director	Oil and energy company
St1 Lähienergia	managing director	Heating solutions company

Motiva	energy efficiency expert	Energy efficiency advisory
Fortum District Heating	country manager	District heating company
Metropolitan Transport Authority	project manager	Public transport authority
LUT University	research director	Power-to-x project manager
Finnish Ministry for Economic Affairs and Employment (TEM)	energy market expert	Government Ministry

We formed a database of interview comments and desk study data on documented events such as entrepreneurial activities and investments. We conducted a qualitative thematic analysis (Miles et al., 2020) by first sorting both the interview and the desktop data into enablers (internal and external enablers separately) of and barriers to investments. The statements were coded and from the initial themes categorised to the relevant TIS functions: resource mobilisation, entrepreneurial activities, market formation, guidance of the search and knowledge development and diffusion. The statements were also categorised to the various TISs within the clean energy sector based on the source and context of the comment. The coding was carried out by the first author and validated by the other authors. The summary of the categorisation is shown in Table 2. The TISs analysed include power production and transmission, electrification in space heating and transport as well as the coupling of the different energy sectors through storages, demand response and power-to-X-technologies. There were no conflicts between the different types of data.

3.2 Context: the clean energy sector in Finland

Finland is an interesting case for analysing the mobilisation of mainstream finance, since it has an ambitious target to be carbon-neutral by 2035 and is doing so from a position where wind and solar power have only recently started to attract serious investment. The traditional energy system has been based mainly on thermal power stations (Figure 3), and wind, solar and hydropower together only accounted for 5% of primary energy sources in 2019 (see Appendix A). This is the case even though renewable energy sources accounted for 37% of the energy: most of this is bioenergy, the share of which cannot be increased substantially without compromising carbon sinks in forests (Cowie et al., 2019) and there are constraints on the expansion of hydropower, as well. Hence, the phase-out of fossil fuels and peat, accounting for 38% of total energy sources, must mainly rely on increased wind power production (given the climate constraints on solar power) and electrification of end-uses (Rinne et al., 2019).

In addition to the carbon-neutrality target, the government has decided to phase out coal in energy production by 2029. District heating plants are major users of fossil fuels and almost half of all residential and commercial buildings are served by district heating (ET 2019). Moreover, transport is still highly dependent on fossil fuels.

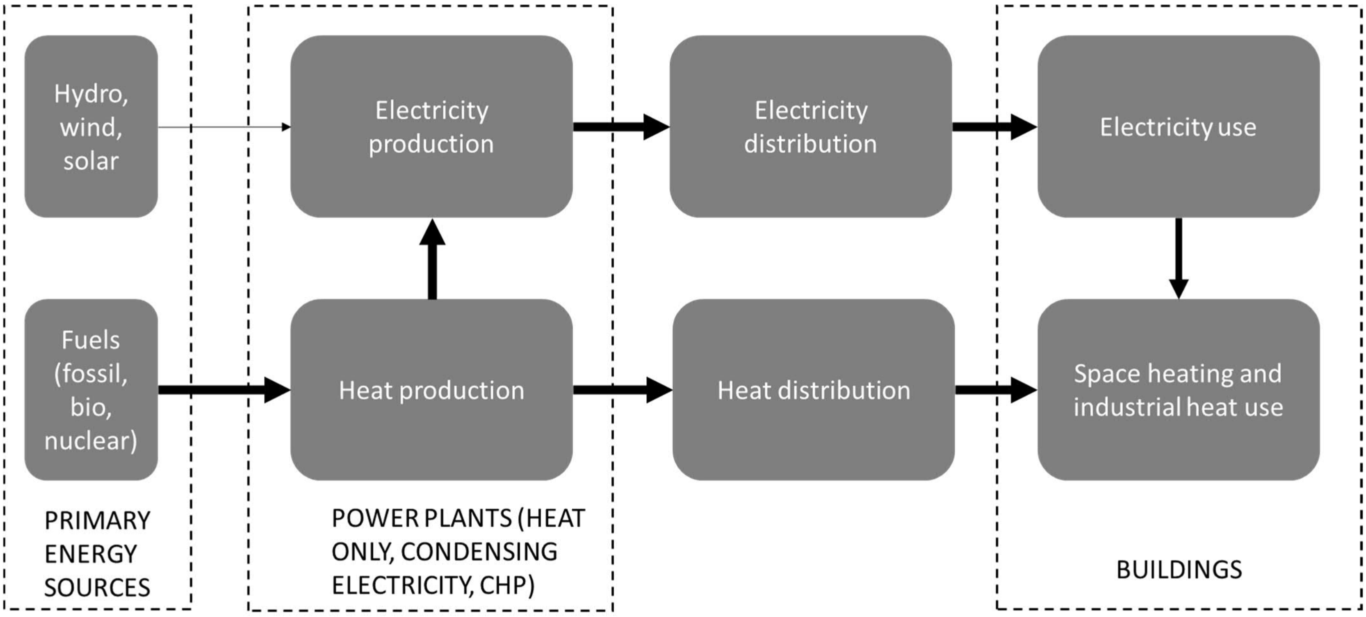

Figure 3. Schematic view of the traditional energy system in Finland. Its typical features are that 1) thermal power stations dominate over hydro, wind and solar, 2) Combined heat and power production dominates in space heating and industrial heat use and 3) Both heat and power production are adjusted to consumption. Fuels for mobility are included in the primary energy sources. The thinner arrow illustrates the minor role of hydro, wind and solar.

An envisaged fossil-free energy system required for carbon neutrality (Figure 4) will be based on an electrification of the energy system, which means that the total power production is estimated to increase from the present 85 TWh/a to 125 TWh/a (Rinne et al., 2019). There is already a shift of focus in energy production towards renewable sources and nuclear energy. CO_2 emissions from energy production have decreased by 26% in 1990-2019 due to a shift away from coal, gas and peat, as well as to increased energy efficiency (Lovio, 2020). A totally fossil-free power production is estimated to require additional installed capacity of approximately 19 000 MW of wind power (Rinne et al., 2019), which appears to be feasible considering estimates based on ongoing projects (Finnish Wind Power Association, 2020), given sufficient power transmission capacity.

In addition, the production of heat in buildings needs to shift from fossil fuels to electric heating sources such as heat pumps, which have proliferated in private households, while industrial and residential scale heat pumps have only recently started to diffuse. The investment needs for a fossil-free district heating are estimated to be ca. 600 M€/a (Rinne et al., 2019), excluding investments in energy efficiency and distributed energy production. The most difficult sector for Finland is transport, where the target of halving the fossil fuel use in transport by 2030 is very challenging, requiring investments by households, companies and the public sector in vehicles and charging infrastructure. In addition, there are major needs to reduce emissions in the heavy industry, mainly steel and chemicals production, but industry, being specific in nature, is not covered by this study.

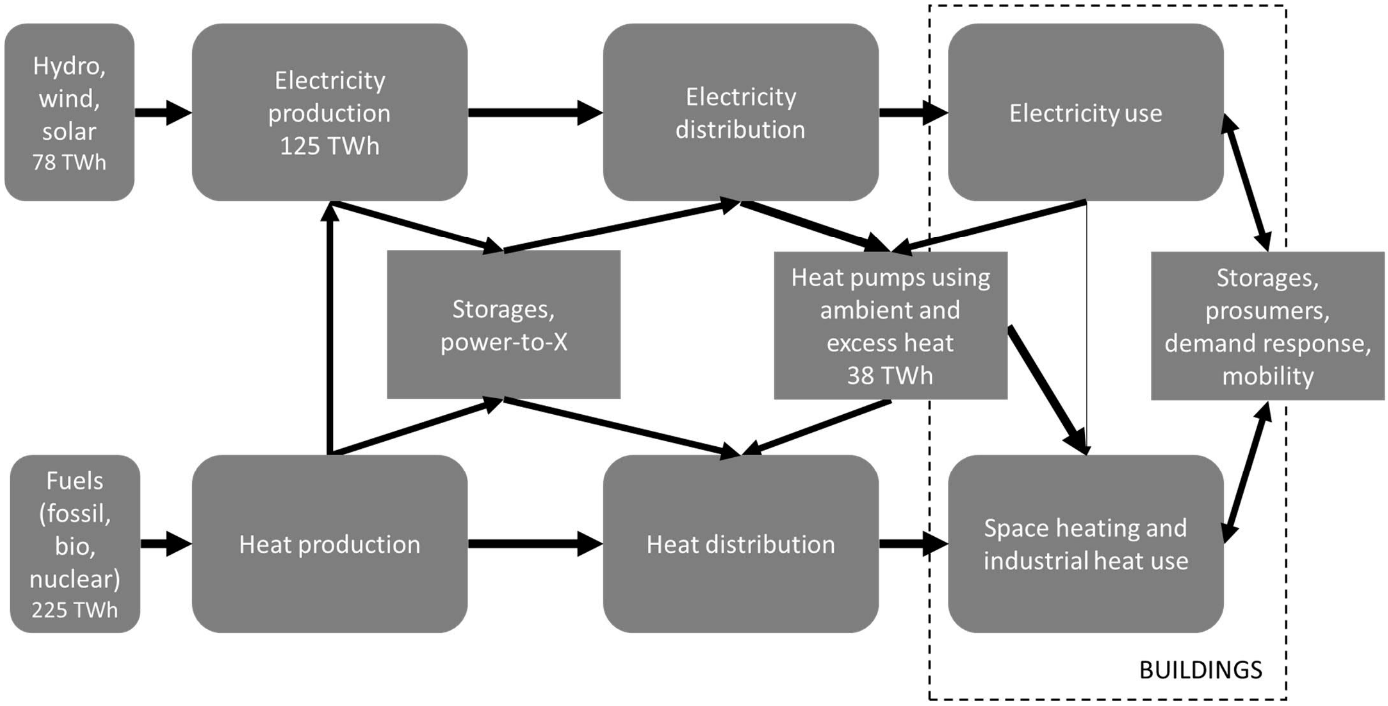

Figure 4. Schematic view of the future energy system, which is used as a reference for the investments needed for the transition. Its features include 1) Intermittent power production supported by storage and demand response and 2) Increasing coupling of the electricity, power and mobility sectors. Energy flows from Rinne et al. (2019).

4 TIS analysis of mobilising finance for the clean energy sector

We present the findings of the study in this section in three parts. First, we present the enablers and barriers in the TIS functions connected to clean energy investments. Second, we describe the roles of developers and financers in the mainstreaming of financing. Third, we show how the three TISs are connected within the clean energy sector and how this affects the mobilisation of mainstream finance.

4.1 TIS analysis for the clean energy sector

The TIS analysis shows enablers and barriers in the various TIS functions. Many of them are recurring in all the studied TISs, but several are TIS-specific (Table 2). The TISs studied vary in their maturity. In the power production and transmission TIS, there are many enablers of market formation and resource mobilisation (investments) suggesting that the TIS is relatively mature. Similarly, the TIS of electrification of heating and transport approaches maturity, but there are several barriers to market formation and resource mobilisation. The TIS of storage, demand response and power-to-X is much more nascent, exhibiting mainly enablers of knowledge development and diffusion and entrepreneurial activities.

Table 2. TIS analysis of the research data. The numbers in parentheses illustrate the number of comments within the code.

		TIS		
TIS function		Power production and transmission	Storages, demand response, power-to-X	Electrification of heating and transport
Knowledge development	Barrier	Technology risk	Technology risk	Technology risk (2)
Guidance of the search	Enabler	Disruptive policies		Disruptive policies
		Support for just transition		Strategy work (2)
	Barrier	Lack of incentive for active search (2)	Lack of incentive for active search	Lack of incentive for active search
Entrepreneurial activities	Enabler	Support for just transition	Experience, experimentation, RDI	Experience, experimentation, RDI (4)
				New business models (4)
				Service business model
	Barrier	Technology risk		Operative risks
				Network barriers (2)
				Lack of legitimacy
Market formation	Enabler	Enabling market conditions (2)		Stable market exists (heat pumps)
				Market pressure
		Policies for market formation (4)	Policies for market formation	Policies for market formation (8)
				Service business model
	Barrier	Stability of market	Stability of market	Stability of market (3)
				High planning cost (5)
		Policy barriers (3)		Policy barriers
Resource mobilisation	Enabler	Financing available /investments take place (8)		Financing available /investments take place (2)
		Special funding (8)		Special funding (7)
		Disruptive policies		Neighbourhood impact
		Company policies		Service business model (3)
				Pressure of policy implementation
	Barrier	High transaction cost (2)	Lack of business model (2)	High transaction cost (2)
		Operative risks (3)		Bankability of small actors
		Policy barriers		Shortage of renewable power
		Write-offs needed		Write-offs needed
		Pandemic hinders fundraising		Lack of special funding

4.1.1 Enablers of the market motor of clean energy investments

The TIS function *guidance of the search* is enhanced by various strategy level activities for the energy transition, for example by the development of roadmaps for carbon neutral businesses or policy goals. The *guidance of the search* function is also enhanced by disruptive public and corporate policies, such as diminishing funding for fossil fuel investment by funding institutions to avoid "carbon risk" as well as the impending coal ban by 2029 and current proposals to increase the taxation of peat.

Various *entrepreneurial activities* are ongoing in the clean energy sector from RDI through experimentation to commercial solutions. The interview data show that there is significant experimentation in the TIS of electrification of space heating and transport, but it is also starting in the TIS of storages and power-to-X-technologies. Heat pumps are adopted broadly by households, and industrial-scale heat pump applications are being developed in the district heating systems. Deep geothermal heat is being piloted, as well as electrical buses. Incumbent energy companies are also developing new technologies and business models. For example, district heating companies are building new IT systems for improved control of more distributed production systems. These are important developments since incumbent companies are more likely to attract finance from institutional investors than new entrants.

Market formation has taken place both due to policy support, but also due to enabling market conditions such as the open market, smart power grids and the well-developed power distribution and transmission system in Finland. Business models for various services such as demand response are slowly developing. The support policies for market formation have included the feed-in-tariff and auctions for wind power, the distribution obligation of liquid biofuels, fuel tax exemptions and subsidies for the purchase of electric cars. In addition, various public financial tools target energy efficiency improvements in single-family homes as well as owner-occupied and rental apartment buildings.

As concerns *resource mobilisation*, capital is available for various clean energy investments when both the project and the actor can be shown to be "bankable". Our data show that investments are taking place especially in power production and transmission. For example, the profitability of the wind power industry has improved considerably due to the increased size of the power plants, the influence of emission trading on electricity prices and the development of permit procedures. In addition, households and other building owners are investing in cost-effective measures such as improved control of heating, demand response, improved insulation, storage or own energy production, using e.g. solar PV or heat pumps. Electrification of transport is also proceeding through users' investments, with alternatively powered vehicles currently forming 20% of the new vehicle purchases (Traficom, 2020). Following EU targets, public transportation is gradually shifting towards electric transport, which has been enhanced in the capital region by public procurement measures. In addition, many investments benefit from special funding such as investments by public investors in more risky technologies to provide leverage to commercial financers. Indeed, it is reported that the high demand for "green" investment has reduced the cost of capital for renewable energy loans and equity investments.

4.1.2 Barriers to the market motor of clean energy investments

The pace of investments is still slow in many areas, which suggests that there are barriers to the market motor of clean energy investments. Despite extensive strategy work and disruptive policies, there is still lack of strong *guidance for an active search* for new solutions, because the existing technologies such as combined heat and power are seen by many actors as superior. There is still further need for knowledge development mainly in the TISs of electrification of heating and transport, storages, demand response and power-to-X. Even incumbents experience difficulties in moving from centralised energy system to more distributed solutions because "*the production most probably will be distributed over several locations. It makes the system more complicated to manage than the traditional system where you have a power plant and then the network*" (district heating company). Clean energy investments also change the proven methods for evaluating feasibility and carrying out the projects. Lacking clear incentives, investors prefer to start projects where the risks are known, such as shifting from coal- or peat-fired to biomass-based district heating plants rather than industrial-scale heat pumps. Similarly, the price premium on renewable energy projects can lead some institutional investors to prefer projects that are not generally perceived as the “greenest”, but are, rather, on the second tier, and hence more reasonably priced.

In addition to the technological challenges, *entrepreneurial activities* suffer from a lack of legitimacy due to problems caused by the new technology for other actors in the network for example the incompatibility of low-temperature district heating systems with construction specifications. *Market formation* in the clean energy TISs is immature, which is highlighted in uncertainty over future power prices, as well as the high purchasing prices, limited supply and uncertain value development of EVs, and the developing status of the EV charging network. There is also uncertainty about policy measures such as taxation and the price of carbon emissions in the EU emission trading system. Uncertainties make it difficult to pick the companies that are likely to win the market in the long term.

Resource mobilisation is hindered by the smaller size of the projects compared to the traditional centralised production, which increases the planning and transaction cost of individual projects, thus reducing their feasibility. This is especially the case in the TIS of electrification of heating and transport where investments are often carried out by households. In addition, the small size of the projects, compared to projects in centralised energy production, limits their attraction for financers. *”The projects in Finland are rather small and their “baskets” are big. If you have a good project worth 20-30 million euro, it is nice, but we would need many times bigger projects than this”*. (Oil and energy company). Moreover, the power sector faces new administrative barriers to resource mobilisation. For example, in the wind power sector, permit procedures cause delays that prevent the developers from keeping up with the technological development. Finally, investments in the district heating system are constrained by difficulties in transforming the business models of the incumbent district heating companies, as well as sunk costs in existing assets.

4.2 Developers and financers bridging over the valley of death

As previously acknowledged, technologies wishing to survive the second valley of death require substantial capital investments (e.g. Karltorp et al., 2017). Incumbent companies in energy production, transmission and distribution have the capacity to carry the risks of developing and investing in large-scale infrastructure projects themselves, but there are only a limited number of such companies in Finland. Incumbents typically rely on traditional funding through corporate equity and bank loans, but green bonds may both bundle a number of projects into a larger financial offering and attract investors.

However, new entrants and foreign investors are for example responsible for 80 % of the wind power investments (Finnish Wind Power Association 2020). The challenges for new entrants include limited creditworthiness as well as the uncertain price of intermittent renewable power. These barriers are often managed through Power Purchasing Agreements (PPA) (where the buyer commits to purchasing an agreed portion of the production for a fixed period at an agreed price), or the traditional Finnish Mankala-company model (a joint stock company formed by energy using companies to jointly own an energy plant, where each shareholder collects a share of the produced electricity or heat corresponding to the share of stocks held). For example, large international companies such as Google or IKEA have closed long-term PPA contracts on wind power and some large Finnish companies (such as UPM, Finland’s largest forest industry corporation) are following their example. Some renewable energy developers have sold their finalised projects to financial institutions after completion to finance their next projects.

The distributed nature of the clean energy sector has increased the role of users as investors bringing new flows of funds to energy investments, also enabled by new forms of funding such as crowdfunding. Various building-sited solutions such as energy efficiency, solar energy, heat pumps and storages are mostly invested in by the users, both households and large building owners such as shopping malls, office buildings and public buildings. The projects are small and scattered and the main challenge is the high relative cost of planning and transaction compared to the size of the project: ”*everybody needs to learn the subject, study* *it and believe that it works…*" (Development bank). Our informants emphasised the need for standardised products and solutions as well as exemplary cases. This does however present challenges as technology providers also tend to be small and lack the resources for developing standard turn-key packages of solutions for different buildings. "*[if] we would get many case examples, we could group different types of buildings and figure out which kind of actions would be the most cost-effective ones in each of them. So we could get a good library of examples to help owner-occupied apartment buildings…"* (Energy efficiency advisory)

One of the emerging solutions to crossing the second valley of death in market development are so called life-cycle models where a credible technology provider invests in the equipment and possibly also operates it and the client gradually pays for the service through various contract models. A service model is able to solve the issues of lack of capabilities, lack of capital and credibility for funding, as is often the case with building owners. : "*[if there is] an actor that understands the operation, believes in it and can and will take the risk… then scale-up and grouping the projects gets easier*" (Development bank).

Financial institutions offer funding either in the form of loan or equity. Carbon risk is a significant factor for banks, effectively preventing lending to projects involving fossil fuels: *"The carbon issue is becoming stricter and stricter all the time for all…"* (Mainstream bank). On the other hand, in loan finance it is not only the creditworthiness of the project but also of the company that counts, since it is the solvency of the entire company that influences its repayment capacity. Investment banks, which collect funds from private investors, consider that there is a general willingness to invest in clean energy, but in order to create a fund, the volume needs to be at least in the range of €100 million, which means that many clean energy projects need to be bundled to create an interesting target for green funding. This is possible for large companies, but smaller actors would need a separate intermediary to package the projects. The small volumes of projects are also a barrier for institutional investors, as are the relatively high costs of investing in "green" stocks and bonds, owing to the sudden surge of interest in such products globally.

In addition to commercial banks offering traditional loans, there are various financial actors with a mandate from e.g. the government to take additional risk in their funding in order to enhance new developments such as climate change mitigation. They often offer partial funding to leverage commercial loans. It was also suggested that they might guarantee green bonds in order to increase their attractiveness to institutional investors by bringing down repayment risks. The involvement of traditional players such as development banks and incumbent companies is important for the increased involvement of institutional investors, for which the risk-return profile and the pricing of financial products is of tantamount importance.

Many clean energy technologies, such as power-to-X and deep geothermal energy, are not yet close to the second valley of death and are still dependent on the public sector funding for development. On the demand side, the role of public procurements of e.g. power transmission, electric vehicle charging solutions and electric buses has proven to support learning and create examples for smaller investors.

4.3 Analysis of the interdependency of TISs in the clean energy sector

The studied TISs appear to be highly interdependent, although they differ in terms of both the stage of development and the typical investors involved. The power production and transmission TIS – in Finland especially wind power – is an example of a TIS in the second valley of death, where the intermittency and cost structure of wind power makes the power price unpredictable and prevents the formation of a stable market. Further growth and profitability of power production depends on the increase in power demand supported by the ongoing electrification in space heating and transport (and in industrial processes, which are not within the scope of this study). On the other hand, the electrification sector is dependent on the investments in the power sector, which is reflected e.g. in this comment concerning the building sector: "*you cannot invest too much in wind power*" (Energy efficiency advisory).

Furthermore, a stable market for renewable power requires a stable market in electrification, which suggests that the TISs are closely interconnected. The electrification TIS is partly in the second valley of death, but partly in earlier stages of development. For passing the second valley of death, technical assistance and standardised solutions are needed to overcome the challenges of small projects. To this end, various public support measures have been introduced. As these projects often take place in the context of general refurbishment projects, even small monetary incentives have been seen to be effective, because they guide the search for solutions within a larger project. Similarly, green building certificates can reduce the cost of capital for professional building owners or purchasers, and hence, their criteria can be important in setting benchmarks. Service business models also encourage building owners to invest in clean heating technologies and energy efficiency without heavy initial investments. Competition from building-sited heat pumps, as well as the increasing cost of fossil fuels, have also launched a renewal of incumbent district heating companies. For the less mature technologies public procurement measures such as initial public investments, procurement criteria and long contract times for private transport contractors have been successfully applied in the electrification of public transport, where the bankability of small transport operators limits the adoption of new technologies.

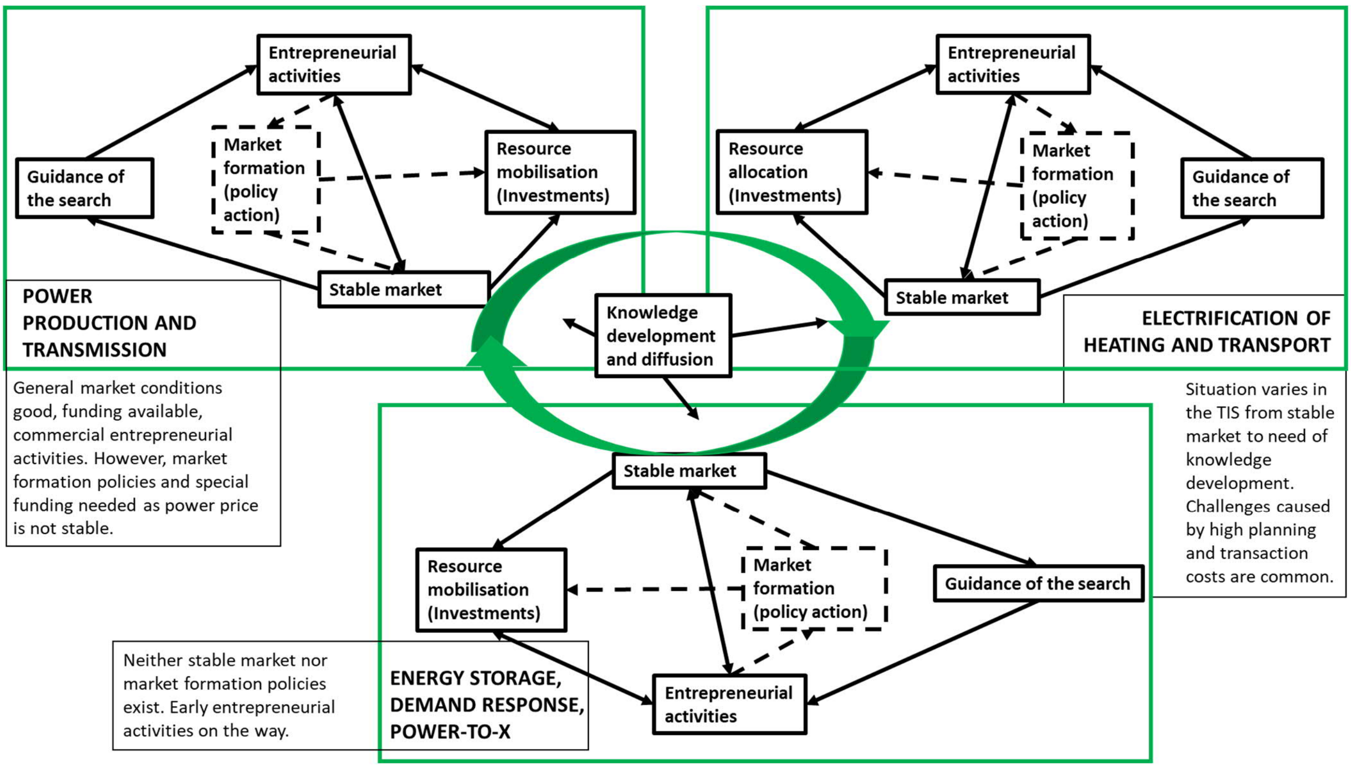

Figure 5. Interconnectedness of TISs in the clean energy sector

In the near future, with increasing penetration of intermittent renewables, the price of electricity is expected to be very low or even negative at times, which may hinder further investments. Storage of energy as electricity in batteries or as heat in various volumes is one solution under development. Simultaneously, the search for solutions for long-term energy storage has intensified. Power-to-X technologies are estimated to have a central role in the European transition to a 100% renewable energy system (SolarPower Europe and LUT University, 2020). The TIS of energy storage, demand response and power-to-X is thus crucial for the profitability of investments in clean power production. This TIS is, however, very far from developing a stable market as there are still barriers even in knowledge development and entrepreneurial experimentation, as well as in market formation, given the dependence of this TIS on the materialisation of periods of low power prices and demand for synthetic fuels and/or industrial chemicals. As long as there are several competing solutions to intermittency, institutional investors struggle to identify future winners. Therefore, the support of this TIS for the development of a stable market for renewable power production is still rather weak.

While financial resource mobilisation in each part of the emerging clean energy TIS has its own dependencies on other functions, such as entrepreneurial activities and guidance of the search toward commercially feasible options on a large scale, there is also a mutual dependence on shared knowledge development and diffusion. While the power and other energy markets deliver information on current prices, in a rapidly evolving market they offer little direction on future energy prices, demand for various products or the relative costs of the capital investments required. Hence, creating a stable market requires increased insight on the future pace of development and cost of clean power production, the future demand for power in e.g. heating and mobility as well as the availability of solutions for power storage. Finance providers also require standard definitions, which are expected to emerge from the EU Sustainable Finance Taxonomy (Regulation EU 2020/852). At present, investors share general and diffuse expectations of a system transformation, which are visible in emerging investments and market formation activities such as the development of new business models to reduce uncertainty, but a consistent market motor combining these different parts of a clean energy sector is yet to emerge.

5 Discussion

In this section, we first discuss the novelty of our findings and the contribution to the TIS literature. We also bring forth the limitations of our study as well as future research needs.

5.1 Novelty of the findings and contribution to previous literature

We contribute to the literature on TIS by illustrating the interdependencies inherent in resource mobilisation for investments in the whole clean energy sector as called for by Markard et al. (2015) and Bergek et al. (2015). The novelty in our approach is that, unlike previous TIS analyses, we have analysed the interdependencies by focusing on three TISs: clean power production, electrification of heating and mobility, and the development of solutions for energy storage (Figure 5). In all the TISs analysed, a significant growth in investments suffers from the lack of a stable market, which is often reflected in prices. In the case of wind power, the instability of the price of electricity, as reported by Wozabal et al. (2018), increases the risk of investments, which has highlighted the role of long-term customer contracts in creating a stable investment environment. We find that the TISs connected to the end use of electricity and the management of intermittency are less developed than the TIS connected to power production, which reduces the predictability of the price of electricity. Therefore, the pace of electrification of heating and transport will affect the demand for power, and the management of intermittency will affect the variability of the price of power. On the other hand, the commercialisation of energy storage technologies is highly dependent on the availability of surplus power to store, and the demand for products acting as storage, such as synthetic fuels. Thus, our study highlights that the development of stable markets in the clean energy sector requires simultaneous maturity of the various TISs, emphasising the interdependencies of the TISs.

We have also shown that while these TISs entail relations between various functions, there are functions that are shared between the TISs, in particular, knowledge development and diffusion and guidance of the search in terms of predictions of the development of future supply and demand for various energy products. Hence, our study underlines that the creation of a common perspective on how the energy sector is likely to develop is critical, highlighting the role of the public sector, particularly in shaping the demand for specific solutions (such as energy storage).

In addition, our findings contribute to the research on clean energy investments by showing a structural change in the financing of energy projects from large projects to a great number of small and scattered projects as the energy system becomes more distributed along with the progress of the energy transition. This requires new competencies from financiers (as suggested by Polzin & Sanders 2020), more resources, as well as massive learning by all actors in the sector on how to plan, standardise and evaluate the feasibility of projects. In addition, the small and scattered nature of projects in the sector increases the learning, planning and transaction costs of individual projects, making it difficult to mobilise capital, which reflects the different logics of the financial sector, in its expectation of large projects, and the energy sector requiring more moderate investments but in several contexts and locations (Karltorp, 2016; Polzin et al., 2016; Polzin and Sanders, 2020). One way to align these logics involves bundling of projects to reach a size that creates interest in the financial sector. Another means of reducing the learning cost is improved learning from experimentation (Heiskanen et al., 2017a), for example involving large actors such as shopping malls to test and showcase new solutions and thus create replicable models for smaller investors.

Therefore, we could confirm the findings of extant research (Polzin et al., 2016; Polzin and Sanders, 2020) that TISs in different stages require different funding. Power production is already passing the second valley of death (Karltorp, 2016). Electrification develops unevenly – some technologies have passed the second valley of death (e.g. heat pumps), some are still mainly funded by venture capital (e.g. deep heat), but power-to-X still requires public RDI funding. Our research provides a novel contribution to the relatively limited literature of TIS analyses on the development of the market motor and passing the second valley of death of financing (e.g. Karltorp, 2016; Karltorp et al., 2017; Quitzow, 2015). At this development stage of the TIS, different technologies compete for finance and most users consider various technological options and even invest in a number of technologies simultaneously. The role of special funding instruments in leveraging mainstream finance in the second valley of death was shown to be important, as reported by Geddes and Schmidt (2020), as was the role of public investment banks in keeping the risk premium of funding reasonable, as suggested by Karltorp (2016).

Following the call of Mazzucato and Semieniuk (2018), we analysed the roles of different investors and financiers in clean energy investment. We found, confirming the findings of Heiskanen et al. (2017b) and Polzin and Sanders (2020), that the energy transition indeed brings forward new types of investors, and thereby new capital into the energy sector. One of the most significant new groups is energy users, either individual households or businesses that use energy, as is the case in Germany (Salm et al., 2016): visible examples of such investments are heat pumps, solar panels and electric vehicles. We elaborate on this by showing how the entrance of the smaller investors in the market is supported by the creation of trust in the market. Creation of trust in new technologies and the project developers deploying them has been enabled by for example purchase agreements with credible actors, supply agreements with credible technology providers and the involvement of special private and public financing institutions with a social mandate to take larger risks. There is also an increasing market for private savings and institutional investment if they are channelled to "green" purposes by innovative and credible actors, which is shown by the success of green bonds and some special funds for renewable energy. We also found that various ways are gradually developing to combine a number of small projects into large packages that are easier to finance. One possibility is to issue green bonds, while another is the packaging of solutions into service business models, which has allowed technology providers to multiply their solutions.

5.2 Limitations and future research needs

There are certain limitations to our analysis. We have only illustrated the interdependency of clean energy solutions in one particular country. The challenge is global, but the particular issues are likely to depend on the structure of each national or even regional energy system (see e.g. Bogdanov et al. 2019). Moreover, within the Finnish emerging clean energy sector, we have only analysed three major components: financial resource mobilisation of wind power production, electrification of heating and mobility, and power-to-X as an example of a solution for long-term energy storage. The TIS framework is suited for qualitative analysis of the development of the mobilisation of resources into technological innovations rather than quantitative analysis of financing.

Future research could focus on the electrification of industrial processes, and our picture could be complemented by a more detailed analysis of the long-term market impacts of different kinds of funds utilised by major portfolio investors. Future research could expand beyond a single country to consider clean energy investments at a European level. Countries in the global south are likely to meet different challenges in finding finance, so future research could also target countries and areas outside of Europe.

6 Conclusions and policy implications

Clean energy investments are extremely dependent on the cost of financing because their cost structure is dominated by the initial investment. However, our findings do not suggest that the amount of funds would be the main limiting factor but bring forward several different aspects of funding that affect the investments. The market for clean energy investments is not yet fully functional without policy support. For example, a stable and predictable price for carbon, smooth permitting processes and public procurement are needed. Public procurement could provide exemplary cases, especially in building-scale solutions such as energy efficiency and help to reduce the development cost of projects by smaller building owners. In the process of the energy transition, only the energy production technologies are close to maturity, but the solutions for energy storage and other flexibility measures would stabilise the energy market. Therefore, the investments are supported by the commitment of large credible customers. In addition, the energy transition has profoundly changed the structure of investments from large centralised projects to include also a multitude of small projects, a way of working which challenges both the energy and the financial sector.

The challenge of the small and scattered nature of clean energy projects requires policy action to reduce the uncertainties and transaction costs. Energy efficiency and energy production investments in individual buildings need measures to enable the multiplication of projects without massive planning. These could include model solutions, standardisation, technical assistance and collaboration between building owners. Especially the role of users as investors has been growing, which will increase the role of technical support and standardised solutions. The alignment of project developers and financiers called for by Karltorp (2016) has been improved through credible customers using business models such as PPA and the Mankala model in the wind power sector. In the small investments in building-sited solutions such new business models combining financing and service models would be crucial for the energy transition but remain underdeveloped.

The role of the state has been and will be crucial for the development of clean energy technologies. Even if today wind power investments are in most cases market based, policies have been important for their development. Various subsidies such as the feed-in-tariff and emissions trading have brought the technology to its present stage of maturity. Moreover, infrastructure has been essential, such as the law-based mandate of the Finnish TSO to ensure adequate power transmission. Policy will also have a role in the future in creating markets for storage and electrification, as wind power developments may face low profitability due to the low prices of both electricity and emissions trading allowances. Consistent long-term policies are crucial for the involvement of institutional investors, which struggle to pick transition winners and survivors under uncertainty. Because of the interdependency of the various technologies in enhancing the energy transition, it is crucial to continue and increase public RDI support to less developed technologies such as power-to-X. Solving the challenges of intermittency management will stabilise the market for renewable energy production. Thus, investments in individual TISs in the clean energy sector are interdependent.

Funding

This work was supported by the Strategic Research Council at the Academy of Finland (grant number 13314325).

Acknowledgements

The authors would like to thank all the interviewed experts for their time and effort in supporting this research. We also thank the five anonymous reviewers for their valuable comments on our manuscript.

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Appendix A. Total energy consumption by source in Finland in 2019 (source: Lovio 2020).

Energy source	TWh	%
Oil	85	22
Coal	25	7
Natural Gas	20	5
Peat	16	4
All fossil fuels and peat	146	38
Wood fuels	105	27
Hydro power	12	3
Heat pumps	7	2
Wind power	6	2
Biofuels for traffic	5	1
Recovered fuel (bio-fraction)	4	1
Other bioenergy (including biogas)	2 (1)	1
Solar energy	0,2	0.05
All renewables	141	37
Nuclear	69	18
Net imports of electricity	20	5
Total	378	100

Appendix B. Reports not mentioned in the reference list but used as data in the desktop study

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