Understanding drivers and barriers for industry formation around re-use and recycling of electric vehicle lithium-ion batteries in Norway

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Abstract

The electrification of road transport is contributing to a rapid growth of the lithium-ion batteries on the market. The Norwegian government targets that all new personal car purchases are low-emission vehicles by 2025 (Ministry of Transport, 2016). Given the intended targets, the government, however, does not have a conclusive strategy for the recycling or second use of retired lithium-ion batteries. Therefore, this thesis aims to gain an understanding of the emergence of battery recycling and re-use around end-of-life electric vehicle batteries. The study employs the Technology Innovation System (TIS) framework with extension to the multi-technology interactions along the value chain.

The results show that battery recycling and re-use TISs meet numerous barriers which require government intervention. Moreover, both TISs are largely depended on the innovation processes along the complex battery value chain and require coordination among different actors and across the upstream and downstream sectors.

Keywords: lithium-ion batteries, electric vehicle, second-life EV batteries, technological innovation system.

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List of abbreviations

BES – Battery Electric Vehicle

DSO – Distribution System Operator

EV – Electric Vehicle

ICE - Internal Combustion Engine

Li-ion - Lithium-ion

LIB – Lithium-ion Battery

OEM – Original Equipment Manufacturer

RES – Renewable Energy Sources

TIS – Technological Innovation System

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1. Introduction

Road transport makes a significant contribution to the concentration of carbon dioxide (CO2) in the atmosphere accelerating climate change. In attempts to reduce greenhouse gas emissions, countries strive to phase out internal combustion engine (ICE) vehicles by promoting alternative transport systems such as public transport (trains, metro, and trams) and individual transport (bicycles and walking). Moreover, a dozen countries worldwide intending to achieve a “green” transportation utopia have already made high-profile statements about plans to ban the sales of passenger vehicles powered by fossil fuels by 2040 (Burch & Gilchrist, 2018). The alternatives to conventional cars become low and zero-emission vehicles including the improved ICE vehicles powered by biofuels, hydrogen fuel cell vehicles (FCVs), plug-in hybrids electric vehicles (PHEV), and battery electric vehicles (BEVs). The latter becomes a common strategy for a transition to clean sustainable automobility among countries. At present, BEVs gain the global momentum and forecasts assume that BEVs sales and stock will nearly double by 2030: sales will reach 43 million, and stock more than 220 million (IEA, 2018).

Among all countries, Norway clearly stands out against the background of world indicators being the leading country with the highest rates of BEVs per capita (IEA, 2018). The significant expansion of zero-emission vehicles in the country has largely been successful due to the comprehensive government policies directed at both acceleration of purchasing and use incentives of BEVs (Mersky, Sprei, Samaras, & Qian, 2016) and at minimizing benefits of owning conventional cars (Figenbaum, Assum, & Kolbenstvedt, 2015). Undertaken interventions have led to an increase in sales of BEVs subsequently contributing to reduction of road-traffic emissions (Røhnebær P.G.; Engeda M.I.A., 2018). Building on this positive development, the Norwegian government targets that all new personal car purchases are low-emission vehicles by 2025 (Ministry of Transport, 2016).

Although the public policies to spur the uptake of electric vehicles bear fruits, and sales in the country are skyrocketing, BEVs´ technological weaknesses still do not allow the market to fully accept them (Egbue & Long, 2012). At the same time, the adoption stimulus, which includes certain tax exemptions, free public parking, free public battery charging, etc., cumulatively provides lower revenues to the Treasury[1]. As a result, the generous fiscal incentives provided by the Norwegian government provoke debates about the pressure on the public purse (Berkeley, Bailey, Jones, & Jarvis, 2017).

Aside from the economic incentives, the purchase of EVs is also caused by the pro-environmental behavior of customers (Rezvani, Jansson, & Bodin, 2015). Moreover, financial encouragement epitomizes a national policy, giving the electric vehicles "a symbolic certification as an environmentally sound mobility choice" (Ingeborgrud & Ryghaug, 2019, p. 170). In fact, due to the high cost and imperfection of the technical characteristics, the only advantage of BEVs over conventional cars is the absence of exhaust pollutants. Therefore, it can be assumed that if there are no obvious environmental advantages of BEVs over fossil-fueled vehicles, and even more so if it is reliably found that BEVs cause more harm to the environment, in that case they will surely miss its social value and completely lose the chance to displace conventional cars in the future.

For this reason, it can be assumed that a supposedly perfect plan of transition to low-emission vehicles has a significant drawback. The lithium-ion battery (LIB), which is a key enabling technology of the green transformation in transport, may just as well become the Achilles heel of the entire strategy. Firstly, the rapid expansion of the BEVs fleet will generate in the forthcoming future large volumes of spent batteries classified as industrial waste, which accordingly raises questions about its management (Gardiner, 2017; Wang et al., 2014). Secondly, production of large volumes of batteries for electric vehicles (EVs) proportionally increases the demand for raw materials (Bazilian, 2018). The critical material bubble may eventually burst, as the environmental damage at the extraction site, monopolistic material supply conditions, and low investment rate in the mining industry creates a pressure on the supply of natural resources.

A large concentration of raw materials required for LIBs production is found in politically unstable countries such as the Democratic Republic of Congo (DCR). Socially irresponsible mining is predominant in the country, including hazardous working conditions and child labor (Amnesty International, 2016). The mining of raw materials also has an environmental impact. For example, the largest lithium resources are concentrated in a so-called *Lithium*

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[1] Johan Sættem - https://www.nrk.no/norge/siv-jensen_-_-har-nedjustert-inntektene-med-3-milliarder-pa-grunn-av-hoyt-elbilsalg-1.14550007

triangle, i.e. Chile, Argentina and Bolivia. A main method of commercial lithium extraction in these countries is a salt brine mining[2] (Prior, Wäger, Stamp, Widmer, & Giurco, 2013). The method is cost-effective since it implies the extraction of lithium from salt-lakes by means of conventional solar evaporation (Liu, Zhao, & Ghahreman, 2019). However, his process requires a large amount of water, despite the fact that the region is one of the driest in the world. Therefore, lithium extraction in the South America area may lead to the depletion of already scarce water supply system in this region and thus, cause damage to the population of nearby communities (Barandiarán, 2019).

Another tension on the global materials market has China with concentration of approximately 50 - 60 per cent of the global cobalt refining capacity (McKinsey, 2018); and more than 65 per cent of the natural graphite mined production (Olivetti, Ceder, Gaustad, & Fu, 2017).The monopolistic market structure of these and other critical materials carries risks for other countries. An illustrative example is how China´s long-term export restrictions on natural resources, explained by domestic natural resource conserving policy, have had an impact on foreign markets and price sensitivity (Charlier & Guillou, 2014; Gavin, 2013). Other aspects of the Chinese local policies such as production quotas, export taxes, and environmental regulations influence and put in jeopardy the global supply chain for raw materials (Mancheri, Sprecher, Bailey, Ge, & Tukker, 2019).

Moreover, all these aspects contribute to the low investment rate in the mining industry what forms another obstacle for sustainable materials supply in the near future (Soon, 2019). Specifically, investments predetermines the whole mining process for small miners which require funding from drilling the exploration holes for new resources to the actual production of raw materials. Although this may not be a concern to large mining companies because they can afford these processes, the low investment rate affecting small miners still influence the industry as a whole. In turn, it can put under the risk the supply of supplementary minerals for Li-ion batteries (Dellan L.G., 2019).

All things considered and given the fact that the entire campaign and the BEVs promotion are based on the assertion that they contribute to the improvement of the environment, a lack of alignment on problems of waste generation and resource depletion could decrease the social acceptance of the BEVs. In other words, a public backlash can reduce BEVs attractiveness

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[2] The second, more costly method, is the hard-rock extraction

and competitiveness vis-à-vis other solutions and disfavor its mass adoption. Therefore, as long as the EVs deployment is considered an action plan for transition to sustainable road transport, policymakers and businesses must start to address the problems of waste and finite resources already now, considering that recycling and re-use of the batteries will be an inevitable part of the solution.

While recycling and r-use of the LIBs are essential to ensure legitimacy for EVs, the introduction of new technologic fields can also create a window of opportunity for new business activities. Driven by the growing market of the EVs and ambitious policy goals to decarbonize automotive sector, the LIB recycling and re-use in Norway can potentially become a lucrative industry and broaden the country´s economic horizons (Frankel D., Wagner A., 2017). The emergence of new industries is especially relevant in the conditions when Norway is moving heaven and earth to weaken its dependence on the dominant oil and gas industry. Transition to a more sustainable low-carbon economy is a complex process involving different social layers with often confronting interests (Frank W. Geels, Sovacool, Schwanen, & Sorrell, 2017). The transformation policies typically encompass both the support of new clean technologies, and phase-out the deeply rooted carbon-intensive industries. The process often implies a political resistance due to the job loss caused by the climate change policies (Fankhaeser, Sehlleier, & Stern, 2008; Frank W. Geels et al., 2017). Therefore, creation of new clean industries and subsequent generation of more green jobs can strengthen the legitimacy of transition policies (Vona, 2019).

A whole complex of the aforementioned aspects of the electrification of road transport indicates that technologies of recycling and re-use are necessary requirements for achieving sustainability. Considering the explicit strategy of Norway to decarbonize the automotive sector (Ministry of Transport, 2016), it is becoming important to understand how can the country prevent the forthcoming detrimental consequences of transport electrification and, moreover, recognize an economic opportunity linked to the new industries. Moreover, battery recycling and re-use have therefore the potential to contribute to the broader transition process of transport decarbonization and legitimate the EVs uptake. Consequently, the understanding of the dynamics of innovations around the technologies of Li-ion batteries at the end of its life in a vehicle will shed light on one of the sides of the multifaceted transformational process. For that reason, this thesis aims to examine the emerging industries around the end-of-life EV batteries related to recycling and re-use in Norway, by asking the exploratory research question:

How can a new industry emerge around end-of-life EV batteries in Norway?

In order to understand the emergence of recycling and re-use in Norway in the context of sustainability transitions, the framework of Technologic Innovation Systems (TIS) will be implemented. The TIS approach is concerned with analyzing the conditions for the emergence of novel technologies and formation of new industries around them. Systematic perspective aims to examine the dynamic relations of different actors, networks and institutions which to some extent contribute to the emergence of innovation and new technology or technologic field (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; Farla, Markard, Raven, & Coenen, 2012; Markard & Truffer, 2008).

The TIS framework will be a basis for understanding processes inherent in the emergence of battery recycling and re-use. In turn, it will provide insight into the mechanisms that trigger or hamper the development and diffusion of new industries around the end-of-life EV batteries. The process of development and technology propagation will to a large extent depend on how the innovation system is structured and how it functions (Bergek, Jacobsson, Carlsson, et al., 2008; M.P. Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007; Markard & Truffer, 2008). At the same time, the innovative processes in the different segments of the complex value chain of LIBs can influence the way how TIS functions. Changes in one component of the EV battery may affect the performance of the rest of the value chain, including battery utilization and recycling. Therefore, it is important to analyze the TIS with regards to the multi-technology interactions, which will be conducted by means of “overlay module” for TIS framework developed by Andresen and Markard (2019).

The overall development of the system can be hampered by a range of barriers such as regulatory, technological lock-ins, lack of financial support, etc. An important role in eliminating the barriers play the public authorities (Elzen & Wieczorek, 2005). By encouraging battery recycling and re-use, policies can provide lucrative opportunities for emerging market players and stimulate the innovation process. Thus, regulatory authorities have a choice to either stimulate innovation or discourage it (Elzen & Wieczorek, 2005). Hence, another reason to implement the TIS framework in this study is to assess the TISs of recycling and re-use and reveal the system barriers. It will further help to identify the key policy issues and suggest policy goals. The governmental intervention could set up the auxiliary building blocks of the innovation system and boost the recycling and re-use development in the country. In the analysis it will be therefore asked following sub-question:

What are the main drivers and barriers for the EV battery recycling and re-use?

And in the discussion, it will be asked:

How can public policy stimulate new industry formation in these areas?

In order to answer the research questions this thesis is organized as follows. Chapter two presents the theoretical framework which was implemented in order to answer the research questions. Chapter three describes the methodological rationale behind the choices of TIS delineation, as well as the methods of data collection. Furthermore, the chapter describes how the conceptual framework was implemented in order to analyze the empirical data. Chapter four provides the empirical background for the study. It includes a brief description of the value chain of the Li-ion batteries and how it performed internationally. The value chain explanation is followed by the scanning of multi-technology interactions. The key processes which drives the innovation in different segments of the value chain will be identified. It will help to understand how they influence the development of battery recycling and re-use from the macro-perspective. Chapter five provides the narrowed analysis of the TISs of recycling and re-use in Norway. First, the structural analysis of both TISs in Norway will identify the actors, institutions and networks engaging in the emergence of the new industries around end-of-life batteries. Secondly, the functional analysis will help to determine how each function of the innovation system works, and evaluate the drivers and barriers of the systems´ development. Finally, the functional pattern will be interpreted in terms of multi-technology interactions specified earlier. Chapter six will, therefore, discuss the results of the study and highlight the bottlenecks in the TISs which might need the policy intervention. Chapter seven will present concluding remarks and suggestions for further studies.

2. Theoretical and analytical framework

As described in the introduction, the overall objective of this thesis is to understand how can new industries emerge around the end-of-life EV batteries with a specific focus on battery recycling and re-use in Norway. In particular, the purpose is to contribute to understanding the underlying processes of industry formation and reveal the drivers and barriers of recycling and re-use development. Analysis will provide a rationale for politicians to stimulate battery recycling and re-use in the country, and eliminate the barriers hindering the process of development, diffusion, and use of end-of-life EV battery solutions.

In order to explore this topic of study, the framework of TIS was adopted in this thesis with extension of multi-technology interactions. The following chapter discusses the overall concept of socio-technical transitions, and present the theoretical perspective of TIS. Further, the discussion will go into the notion of TIS performing in different contexts. Finally, the conceptual analytical tool will be presented.

2.1. Socio-technical transitions

The transformation of the automobile industry in terms of replacement of fossil-fueled cars by BEVs reflects the process of socio-technical transition which is understood as a major systematic shift from one socio-technical system to another (F. W. Geels, 2005). Analytical concept of socio-technical system as such represents a social service-oriented sector (e.g. energy supply, food or transportation) which is created by several social groups such as firms, research and academia institutions, state authorities and users (Markard, 2012). The socio-technical system contributors often have different interests, visions, strategies and resources. This implies that socio-technical transition is always an interactive multi-actor process which endures power struggles, political and common public debates, commercial transactions, etc. (F. W. Geels, 2005). Historical examples of socio-technical transitions are the changes in technologies, regulations, consumer preferences that accompanied the shift from horse-drawn carriages to automobiles, move from cesspools to sewer systems, and substitution of sailing ships by steamships (F. W. Geels, 2005; Frank W. Geels, 2002, 2006).

Socio-technical transition towards sustainability is a goal-oriented fundamental and disruptive change aimed at overcoming the air pollution, road congestion, water scarcity, CO2 emissions and many other challenges affecting different sectors (Frank W. Geels et al., 2017; Markard, 2012). Because sustainability transition is a complex and long-term goals process it requires coordination and joint actions of numerous actors, where political, regulatory and institutional support will play a central role (Markard, 2012). As for example transition in the transportation sector requires not only the technology development of Li-ion batteries, but primarily change in social routines, beliefs and preferences, and intensive government interference (Nilsson & Nykvist, 2016).

Sustainability transitions can be studied from different angles, and the starting point for research can be either a social problem or a possible solution for it (Loorbach, Frantzeskaki, & Avelino, 2017). There are several theoretical foundations studying transitions towards sustainability which often aim to understand and interpret the transformation processes of the changeover from fossil fuels to renewable energy sources. Additionally, given the fact that the sustainability transition is a goal-oriented process, researchers attempt to comprehend how this process can be governed and accelerated (Elzen & Wieczorek, 2005; Grin, Rotmans, & Schot, 2010; Markard, 2012).

The framework adopted for this research is the Technological Innovation Systems (TIS) which is one of the approaches to study specific aspects of transitions. The TIS approach is primarily intended to analyze and explain the emergence and development of new technologies and associated industries. The framework, however, does not cover all the aspects of socio-technical transitions which involve changes in multiple, interlinked technologies and industries, including their maturing and decline (Markard, Hekkert, & Jacobsson, 2015). However, it coincides with the overall objective of this thesis, namely, to understand the stage of preliminary development of the recycling and re-use industries around the spent Li-ion batteries in Norway. Moreover, as discussed in Chapter 1, management of the end-of-life EV batteries, being an important stage in creating legitimacy for electric vehicles, constitute a single part of the multifaceted transition to low-carbon transport. On top of that, the TIS approach provides an appropriate analytical tool to discover the bottlenecks in the industry at the infant stage. This will provide the justification for recommendations on policy interventions.

2.2. Technological Innovation Systems

Technological innovation system (TIS) perspective emanates from the innovation systems (IS) theories which recognize that innovation processes never occur in isolation but continually depend on the encompassing settings. It implies that firms and companies innovate in conjunction with knowledge, information, and competencies exchange with other profit (suppliers, users, competitors) and non-profit entities (universities, government ministers, R&D organizations) (Edquist, 1997; Fagerberg, Mowery, & Verspagen, 2009). Furthermore, the performance of the firms is to a large extend conditioned by the institutional context that by means of laws, funding schemes, social norms and beliefs, technical and environmental standards, provides incentives or creates barriers for innovation (Edquist, 1997).

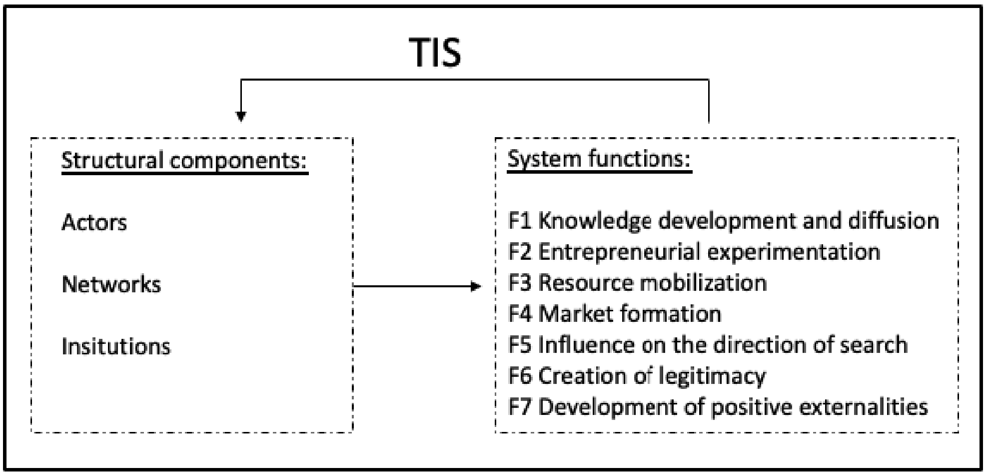
By definition, the concept of TIS implicates an interrelated set of elements such as actors, networks, and institutions, which interact in terms of a certain technological domain and contribute to the innovation process for generation, diffusion, and deployment of a new technology (or industry) (Bergek, Jacobsson, Carlsson, et al., 2008; Marko P. Hekkert & Negro, 2009; Markard & Truffer, 2008). According to Bergek et.al. (2008), the interaction between actors is very weak and often unintended during the formative stage of development. Moreover, actors often have different objectives. But even if they share the same goal, they might not deliberately work towards it (Bergek, Jacobsson, Carlsson, et al., 2008). The interactions between actors can be defined in terms of system functions which represent a set of key processes within the system. Functions are important for the system to escalate and efficiently operate (Bergek, Jacobsson, Carlsson, et al., 2008; M.P. Hekkert et al., 2007). Therefore, functional approach serves as an analytical tool to assess TIS performance and identify barriers and drivers of the system.

Evaluation of the system helps to reveal the weaknesses in its performance and identify key policy issues, thus, providing justification for policy-makers to stimulate development of new technologies and industries (Bergek, Jacobsson, Carlsson, et al., 2008; Jacobsson & Bergek, 2006, Markard et. al., 2012). Therefore, stepping aside from the principles of neo-classical economics, the theory of innovation systems complements the "market failures" arguments for policy interference with the "system failures" (Weber & Rohracher, 2012). According to the neo-classical economics, market failure represents a situation in which free market is unable to coordinate the efficient use of resources. Externalities, monopoly power, public goods, missing markets, asymmetric information are the most mentioned ineffective situations. In accordance with this approach, the economic role of government is to intervene where markets are unable to efficiently and fairly distribute resources. And, therefore, each type of market failure involves a certain type of government intervention (Stiglitz, Rosengard, 2015). However, market failures rationale for policy intervention is not sufficient to identify the key policy issues and does not take into account the possible weaknesses of the networks and institutions. In this regard, focusing on the dynamic nature of innovations, TIS perspective allows to identify weak points of the entire system and indicate the central policy problems for interference to stimulate the generation and diffusion of specific technology or industry (Jacobsson & Bergek, 2006).

2.1. Structural and functional analysis

The assessment of innovation system consists of two major steps which aim to determine the structural components of the innovation system in focus, and to evaluate the system functions, i.e. the internal activities and innovation processes performed within the system by actors and institutional conditions (Figure 2.1).

Figure 2.1. The scheme of analysis (adapted from Bergek et.al.,2018)



First step implies the evaluation of the system components which revolve around a certain technology or industry. As mentioned previously, the structural components of the TIS imply actors, institutions, networks and technology infrastructures. *Actors* imply firms which represent upstream and downstream of the value chain, as well as knowledge generation institutions (universities and educational institutions, R&D organizations), governmental bodies (ministries, financial support organizations), standardization organizations, etc. Formal and informal *networks* as a second structural component of the TIS, relate to the partnerships between scientific community and industry, supplier groups with common customer, industrial and environmental networks and associations. As well as networks, *institutions* can be formal and informal. Formal institutions include laws, rules and regulations that are imposed by authorities, whereas informal institutions are the result of actors´ interactions and include customs, routines, and societal visions (Bergek, Jacobsson, Carlsson, et al., 2008). Since the mapping of informal institutions is problematic, the analysis usually focuses on laws and regulations that have an influence on the TIS. Institutions and actors mutually influence each other. While institutions determine the behavioral patterns of actors, limiting or giving a green light to their actions, actors as such can equally affect the framing of institutional structures (Musiolik & Markard, 2011).

The next phase of the enquiry is the analysis of internal innovation activities conceptualized as *the innovation system functions.* The functional approach allows systematically map the determinants of innovation, assess strengths and weaknesses of innovation processes, and identify policy targets (Bergek, Jacobsson, Carlsson, et al., 2008; Marko P. Hekkert & Negro, 2009; M.P. Hekkert et al., 2007; Markard & Truffer, 2008). The functions may vary and be altered according to the TIS in focus and specifics of the industries, but there are seven central functions (Table 2.1) which are commonly used and are recognized to be inevitable for the innovation system performance (Bergek, Jacobsson, Carlsson, et al., 2008; M.P. Hekkert et al., 2007).

Table 2.1. *System functions*

Function (F)	Description
F1. Knowledge generation and diffusion	The ability of innovation system to generate, disseminate and implement the knowledge base. The analysis provides an insight into whether the TIS has a capacity to adapt and apply knowledge that has already been established globally, i.e. the mechanisms of learning; as well as the ability to eventually amplify it and spread throughout the entire system (Bergek, Jacobsson, Carlsson, et al., 2008).
F2. Entrepreneurial activities	The performance of innovation system depends on the involvement of entrepreneurs and their activities in knowledge exploration and exploitation (M.P. Hekkert et al., 2007). Their activities involve experimentation and demonstrations aimed at identification and evaluation of new technological or organisational opportunities (Bergek, Jacobsson, & Sandén, 2008; M.P. Hekkert et al., 2007, Suurs, 2009).
F3. Influence on the direction of search	The extent to which actors are incentivized or induced to enter the innovation system. Factors which may steer the directionality are the positive expectations; the actors´ assessment of new opportunities within their current technological capabilities; government restrictions or formulation of strategies towards the changing environment (Bergek, Jacobsson, & Sandén, 2008; M.P. Hekkert et al., 2007).
F4. Market formation	The formation of a market is necessary for commercialization of new products or processes. The early stages of market development is characterized by the small size and high level of uncertainties. In order to understand the market formation, there is a need to analyze the drivers and constrains for market development, including the demand side and institutional stimuli (Bergek, Jacobsson, Carlsson, et al., 2008)
F5. Resource mobilization	Especially at the formative stages, innovation system needs an access to human resources, i.e. competencies, financial capital, and complementary assets such as infrastructure and

	complementary products and services (Bergek, Jacobsson, Carlsson, et al., 2008).
F6. Legitimacy creation	Legitimacy is necessary for formation of new industries, and is a matter of social acceptance and obedience to relevant institutions. Legitimacy is shaped by individuals or groups of actors, and characterized by the formation of expectations and a market, regulatory alignment, taxation and financing schemes (Bergek, Jacobsson, & Sandén, 2008).
F7. Development of positive externalities	The development of positive external economies that contribute to the built up of the TIS. External economies can be conveyed through pooled labor markets, the emergence of intermediate products and services, information flows and knowledge spillovers. The function works through reinforcement of other system functions, and can indicate the overall dynamics of the innovation system (Bergek, Jacobsson, Carlsson, et al., 2008; Bergek, Jacobsson, & Sandén, 2008).

Source: modified from Bergek, Jacobsson, Carlsson, et al., 2008; Bergek, Jacobsson, & Sandén, 2008; M.P. Hekkert et al., 2007.

A specific peculiarity of the system functions is that they do not perform in isolation. In contrast, functions interact with each other and co-evolve creating positive or negative bonds. The positive reciprocity contributes to the successful development and performance of the entire IS. Negative interactions between the system functions, in turn, hinder the formation of a full-fledged system and may lead to its breakdown. The functional patterns vary depending of the TIS in focus, however, may acquire similar sequence of effects (Negro & Hekkert, 2008). To exemplify, the favorable interactions between the functions may appear beginning from the “influence on the direction of search” (F3) through the government obligations to achieve particular targets of the GHG emissions reduction by means of renewable energy technologies. The strategic goals of the government will lead to the “resource mobilization” (F5) through the funding of the R&D projects for search of new solutions, what, in turn, will “generate knowledge” (F1) within specific technologic fields. The accumulation of knowledge decreases the level of uncertainties what will lead to the higher level of “entrepreneurial activity” (F2) and “market formation” (F4).

However, an opposite effect may occur through the negative relations between functions. For instance, the implementation of new technologies may require “resource mobilization” (F5) in the form of setting of necessary infrastructure. The lack of infrastructure may influence the “market formation” (F4) for new technologies, and additionally destruct the “legitimacy creation” (F6). Overall effect of poor function interaction will be the accumulation of uncertainties which, in turn, will constrain entrepreneurs from exploration and experimentation activities (F2). Therefore, under such circumstances and without appropriate policy intervention at several functional levels, the innovation system may be restrained to develop and mature.

According to Bergek et.al (2008) an important aspect to remember when analyzing TIS functional patterns, is the fact that the performance of functions is determined by the phase of the TIS development. While Bergek et.al. (2008) have distinguished development and growth phase of TIS development, Markard et.al. (2018) have specified additional two phases of TIS life-cycle, namely the mature and decline phases. The functional performance of the development phase of TIS may differ from the functional patterns in growth, or decline phases. For example, the formative phase is not characterized by rapid growth in economic activities or immediate technology diffusion. Therefore, the assessment of system functionality should be performed with respect to the requirements of the phase of development (Bergek, Jacobsson, Carlsson, et al., 2008; Markard, 2018).

2.2. TIS in contexts

While TIS framework helps analyze new technology and the formation of innovation system around it, scholars have admitted the importance of interplay between TIS in focus with other innovation systems and larger related context (Bergek et al., 2015; Markard & Hoffmann, 2016; Markard & Truffer, 2008). For example, the interplay with external to the system complementary, competing or incumbent technologies can have a different effect on dynamics within a TIS of interest (Markard & Hoffmann, 2016; Negro & Hekkert, 2008). The understanding that technologies evolve differently depending on the surrounding environment led to discussions of how the contextual dynamics influence the development of focal TIS (Bergek et al., 2015).

In attempt to reveal the interaction between TIS and surrounding it context, Bergek et.al (2015) have distinguished several generic contextual structures. Firstly, the external to the TIS environment may imply other technologies which compete or complement each other in various ways (Markard & Hoffmann, 2016). Different technologies might also overlap at different levels of value chain, for example share same production processes or applications (Sandén & Hillman, 2011). Therefore, as Bergek et.al. (2015) noted, interactions occur in the context of other TISs, typically along the vertically related technology value chain. The interplay may be expressed through the interdependence between focal technology on suppliers of the technological components and vice versa. For example, in case of Li-ion battery, the development of cell chemistries will reflect on the battery pack design. Change in the cell chemistry may also influence EVs TIS. Due to the concerns of the conditions under which cobalt has been extracted (e.g. hazardous working conditions and use of child labor), the removal of the cobalt from the cell chemistry would increase the legitimacy of the EVs. Therefore, this type of interactions typically has a complementary implication (Bergek et al., 2015). The interactions may also occur between focal and horizontally related TISs and usually have a competitive connotation. These are the conditions under which TISs have to share the inputs or produce similar output as the focal TIS (Bergek et al., 2015). For example, Li-ion battery competes with the hydrogen fuel cells because both technologies provide the same service of being applied in “clean” automobiles. Therefore, innovation and development in one technology will require innovative response from the other in order to survive the competition.

Secondly, the interaction may occur between TIS and other related sectors. In this case, sector is defined in terms of “production, distribution and use of technologies and products needed to serve a certain function for prospective users” (Bergek et al., 2015). The rationale behind the notion of TIS sectoral context is the perception that a physical artifact has a specific technology architecture and constitutes a complex hierarchy of nested parts (Murmann & Frenken, 2006; Sandén & Hillman, 2011). To put it differently, a single technology can be a combination of different technologic elements and sub-elements, as if Russian matryoshka dolls are composed of multiple nested doll components. These technology elements are produced by other TISs. The technology producing and technology using sectors differ in innovation behavior, institutional policies, and geographic location. Yet, they remain interdependent and development in upstream TISs may affect the development of the focal TIS. The same as changes in the focal TIS may influence the developments in downstream TISs (Bergek et al., 2015; Stephan, Schmidt, Bening, & Hoffmann, 2017).

Moreover, the structural components, i.e. actors, technologies and institutions may perform in several different sectors. Such conditions may have different effects on the development of the focal TIS (Bergek et al., 2015). For example, the actors operating in several different sectors may exchange the knowledge and bring their experiences from one sector to another. Such allocation of structural components creates linkages between the focal TIS and other TISs. (Bergek et al., 2015).

The role of the different sectors in the development of the focal TIS was also studied by Stephan et.al. (2017). By empirical analysis of the lithium-ion battery the authors have explored how the sectoral differences and the cross-sectoral interplay in a multi-component TIS might affect its functions. They assume that a TIS related to a large number of divergent sectors might have multiple sectoral boundaries which need to be overcome in order to avoid the obstacles which inhibit the development of the entire system. The smooth development of the TIS, might therefore require coordination within a specific sector, as well as cross-sectoral interaction. Understanding the roles of the sectors embedded in emerging TIS can also help to reveal the potential bottlenecks and advance specific cross-sectoral policies that will foster TIS development (Stephan et al., 2017).

2.3. Multi-technology interaction along the value chain

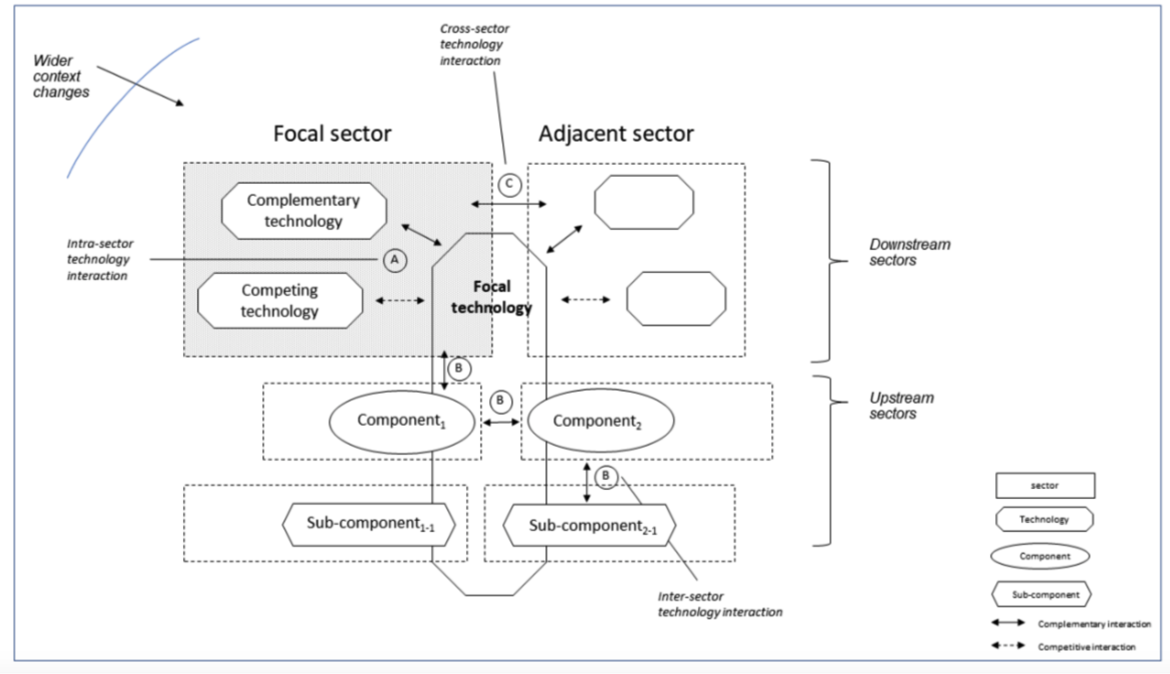
As mentioned earlier, Stephan et.al. (2017) have already employed the case of the LiBs, reflecting on how the sectoral configurations along the value chain of this technology influence the function of knowledge development within the focal TIS in Japan. The scholars have highlighted the importance and need for understanding the spatial and sectoral dimensions in the study of a new technology. They demonstrated that some sectors require support and coordination, especially when the new ones need to be built up. Therefore, there is a need to understand the multi-technology interactions in order to pinpoint potential bottlenecks and employ certain policies (Stephan et al., 2017). This thesis is built on the same approach but with extension and the focus on the second-life and recycling of the LiBs.

Addressing the role of complex multi-technology interactions in transition studies scholars Andersen and Markard (2017) have recently developed an analytical “overlay module” for TIS and MLP frameworks. In combination with TIS, the multi-technology interaction analytical tool is useful for mapping a complex technology value chain, as well as revealing important linkages and interactions between different technologies and sectors.

Authors identify three types of multi-technology interactions. First and central type for this study is technology interaction between upstream and downstream sectors, or *inter-sector interaction*. This type of interactions is inevitable due to the interdependencies between different segments of the value chain. The major changes at one level of technology must often be adapted by changes at other levels to avoid the bottlenecks. Sectoral differences in innovation practices, knowledge development and diffusion, market structure, and institutions create imbalances for development of focal technology. Therefore, the coordination and alignment between sectors is required (Andersen & Markard, 2017; Stephan et.al. 2017).

Another type of interactions is technology interactions within a focal sector[3], or *intra-sectoral interactions.* Several technologies utilized in focal sector are often interdependent, that is, they either complement each other, or compete. Subsequently, innovation and performance improvement in one technology requires innovative reaction from other technologies (Andersen & Markard, 2017). Finally, *cross-sector interaction* occurs between focal and adjacent sectors, and often requires coordination and alignment as integration of the focal technology in several sectors may improve its development and diffusion (Andersen & Markard, 2017). On the top of these three types of multi-technology interactions, Andersen and Markard distinguish complementary and competition interactions. The schematic representation of a focal technology additionally includes the division between upstream and downstream sectors (Figure 2.2.).

Figure 2.2: *Map of multi-technology interaction and associated sectors*



Source: Andersen& Markard, 2017

Andersen & Markard (2017) emphasize the importance of multi-technology interactions in transitions by explaining that inter-, intra, and cross-sector interactions are interwoven, meaning that inter-related technologies and sectors create one large technological system, or “development block”. A development block describes how a combination of core innovations

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[3] Focal sector here, is where the focal technology is applied

engender structural tensions across the value chain, which in turn, can be resolved by complementary innovations. This continuous process of appearing structural tensions and responsive innovative resolutions allow the technological system to evolve further (Haley, 2018). Thus, multi-technological interactions and structural tensions become a crucial mechanism in transformation processes, and therefore for transitions (Andersen & Markard, 2017).

In the next chapter it will be presented how the analytical framework of multi-technology interactions in conjunction with the TIS approach will be applied to study recycling and re-use of the EV batteries in Norway. It will help to understand the type of interactions between different sectors of the value chain, and which of them are relevant and important in the Norwegian case. It will further help to identify the "blocking mechanisms" that restrain the system development, as well as formulate the policy intervention suggestions.

3. Methodology

This chapter presents the methodological choices for the empirical analysis for the current thesis. First, the chosen research design and method for this study will be presented. Secondly, it will be explained how the theoretical framework have been operationalized, including the rationale behind the focus of the current study and the scheme of analysis of empirical data. Further, the data collection methods will be discussed followed by the deliberation of the reliability and validity of the study. Finally, the chapter will be concluded with discussion on ethical considerations and limitations of the research.

3.1. Research design and method

This thesis focuses on the Li-ion batteries in post-vehicle life with an objective to understand and assess prospects of seeing an emerging industry in Norway around EV battery recycling and re-use. To analyze the process of industry formation, I apply an extended version of the TIS framework. I apply a qualitative case study because it is the most common method used in the TIS studies. Moreover, due to the emerging nature of recycle and re-use industries in Norway, there is no sufficient quantitative data to apply for the study. The method was also chosen as it will help to gain understanding of the processes occurring around the end-of-life EV batteries.

Moreover, I apply an embedded single case study design which indicates several sub-units of analysis within a single case study. In the frame of this thesis, a single case, and subsequently a focal technology, is an EV LIB technology value chain with embedded sub-units of analysis of battery recycling and re-use. The more detailed explanation of the choice of focus of analysis will be presented in the next sub-section. The method, however, is challenging. For example, a researcher might fail to return to the larger unit of analysis by giving more attention to the sub-units of the study, so that the holistic features of the case begin to be ignored (Yin, 2009, pp. 46-52).

3.2. Operationalizing theoretical framework

3.2.1. Focusing the analysis

This sub-section explains the methodological rationale behind the focus of this study which is the LIB post-vehicle life, namely the recycling and re-use in Norway. The delineation of the boundaries of a technological innovation system and identification of the relevant contextual structures considered to be one of the most challenging and important analytical choices of a study (Bergek, Jacobsson, Carlsson, et al., 2008; Markard et al., 2015)The complexity of system studies is that the empirical world should be delimited, while in reality there are no boundaries. When studying social structures, it is necessary to decide what actors, activities, and resources to include and which inter-relations to consider. Any enlargement of these boundaries will lead to new contextual and functional interdependencies within the system (Dubois & Gadde, 2002, p. 557). Therefore, the decision-making process is iterative and requiring re-evaluation throughout the analysis (Bergek, Jacobsson, Carlsson, et al., 2008; Markard et al., 2015).

Given the earlier identified social, environmental and technological problems associated with the expansion of electric vehicles and, consequently, lithium-ion batteries, this thesis is aimed at understanding technologies that can help prevent waste generation and relieve pressure on natural resources, thereby adding legitimacy to EVs proliferation. The initial focus of attention was the recycling of lithium-ion batteries from electric vehicles. However, in the process of the literature review, it became clear that prior to recycling, which is often seen as a default solution to the problem of waste generation and scarcity of raw materials, there are promising opportunities to re-use batteries in non-vehicle applications. Moreover, immediate recycling might be a less environmentally efficient solution than utilization of the post-vehicle batteries due to its high residual value. The second-life battery applications grow rapidly and gain the momentum in the industrial, institutional, and scientific circles. The wider implementation of end-of-life LIBs will have a certain effect on the battery recycling industry.

Therefore, in order to understand innovation system of battery recycling, it is equally important to bring into focus the battery second-life applications. These considerations influenced the decision to implement embedded single-case design of study, where EV LIB is a single case with TISs of recycling and re-use as two units of analysis.

The next important for this study factor to consider is the assumption that a single technology is often a combination of other technologies at other levels such as technologic components and sub-components which all together constitute a technology architecture. On the basis of such hierarchy a technology value chain can be identified. Different parts of the technology value chain are often produced by different sectors / industries. The interdependencies between components and sub-components therefore lead to different forms of inter-sectoral relationships. There is therefore an interplay between the evolution of a particular technology and the sectors involved in its production and use (Andersen & Markard, 2017; Stephan et.al., 2017). Li-ion battery is an example of a multi-component product where there are important relationships between different components and associated sectors. Hence, in order to understand the emergence and development of innovation systems of battery recycling and re-use, next to the TIS analysis the multi-technology interactions analytical tool will be applied.

In addition, the study area has geographical boundaries. Namely, the sectors in which the technology is used for commercial purposes (that is, the transport and electricity sectors), as well as recycling and re-use, are delimited to the boundaries of Norway. The Norwegian government strategies and market expectations in these sectors will have an effect on development of the recycling and re-use TISs in the country. At the same time, the rest of the supply chain is viewed internationally. This choice stems from the fact that the Li-ion battery components and sub-components are manufactured outside of Norway, but innovation and development of these technologies are important for recycling and re-use in the country. The geographical delimitation of this study has also a practical justification. Namely, the limited time and size of research, as well as the accessibility of the interviewees, have determined the choice of a single country, in this case Norway.

Finally, the time boundary for this study is the last decade up till the present year of 2019[4]. Returning to the focus of this study it is worth to remind that the attention is on the formative stage of the TIS development which is a process by nature. While this thesis concentrated on

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[4] Although the Norwegian R&D and commercial projects on recycling and re-use of the EV batteries are not older than two years

the process which have to come to an end, the process in reality continues. Bergek et.al. (2008) noted that "we rarely escape formative periods that are shorter than a decade" (p. 419). Therefore, this thesis aims to understand a contemporary process of innovation system formation. This implicates that the conclusions regarding the characteristics of the TIS development reveled in this study are specific to the given period of time and might change in the near future (Dubois & Gadde, 2002, p. 557).

3.2.2. Zooming out the technology of LIB

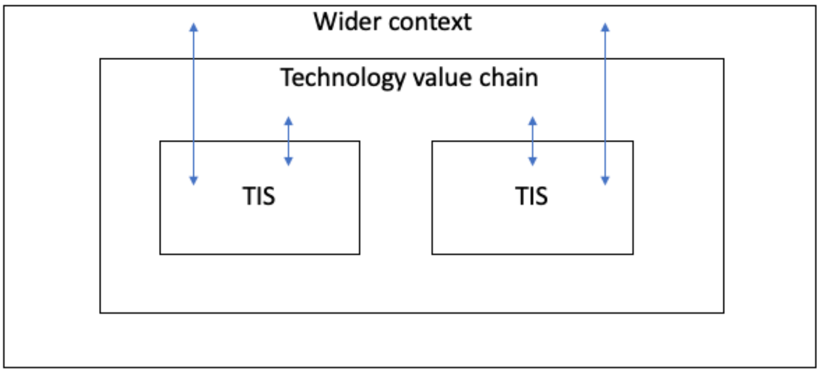
Because technologies consist of other technologies, a TIS analysis has the flexibility of being able to zoom both in and out on a particular focal technology. This means that a TIS analysis could be done at the entire EV Li-ion battery value chain or on a particular component or subcomponent. In this thesis I apply this understanding to move between different technology levels to understand their interactions.

Chapter 4 presents the LIB technology value chain on the international level. This description illuminates the market developments of the technology components, involved sectors, innovation activities, as well as an overview of geographic accumulation of the (sub) components production. It will help to identify key innovation processes driven by the wider context. Considering these implications, the first step of the analysis is to interpret the value chain of LIBs with the help of the analytical tool developed by Andresen and Markard (2017), namely to present a "technology map". The objective is to schematically represent a comprehensive overview of the LIBs lifecycle from its production until recycling. The analysis will help to identify LIB technology components and sub-components within the upstream (sectors where the essential sub-components of the technology are produced) and downstream sectors (the sectors where the focal technology is applied). This schematic elucidation will provide the ground to identify and analyze the key interrelated processes and follow the linkages between different technology components in different sectors. The next step of the analysis is intended to "zoom in" from the overall LIB value chain to focus on the electricity and waste management sectors in Norway, specifically on the emerging battery re-use and recycling TISs.

With this approach my focal units of analysis are two TISs related to re-use and recycling in Norway. These are embedded in three levels of context: (1) the sectors wherein the focal TISs are located (electricity and waste sectors), (2) the Norwegian geographic context, (3) the wider EV LIB value chain which is international, and (4) lastly a wider 'landscape' context.

In my analysis I use the linkages between different context elements and my focal TISs to understand the strength and weaknesses of functions and to identify system failures. The revealed during the analysis system bottlenecks will subsequently be proposed for consideration as recommendation for policymakers (Figure 3.1).

Figure 3.1. *Zooming in and out the technology*



3.2.3. Structural analysis

The structural analysis is intended to identify the components of TISs, i.e. actors, networks, institutions which are actively engaged in the emergence and development of the innovation system. Structural analysis will provide an insight into the industrial players; ongoing R&D and commercial projects; knowledge institutions; governmental policies and regulations; financial support organizations which engage in the TIS formation in Norway.

3.2.4. Functional analysis

The objective with functional analysis is to determine the strength of each function, the overall of the functional pattern[5]. In order to achieve the goal, the interviewed were asked about their perceptions, visions, and expectations of each function. The analysis of the interviews was enhanced by the supplementary analysis of the related documentation. Furthermore, the overall functional pattern will be interpreted in the light of the multi-technology interactions in order to discern the system drivers and barriers. Finally, revealed bottlenecks will be suggested as potential areas for policy interventions.

To summarize, the conceptual framework is operationalized in several steps (Figure 3.2). First, the technology value chain is schematically presented in a “technology map”. The second step is to analyze the value chain in order to reveal the aggregated multi-technology

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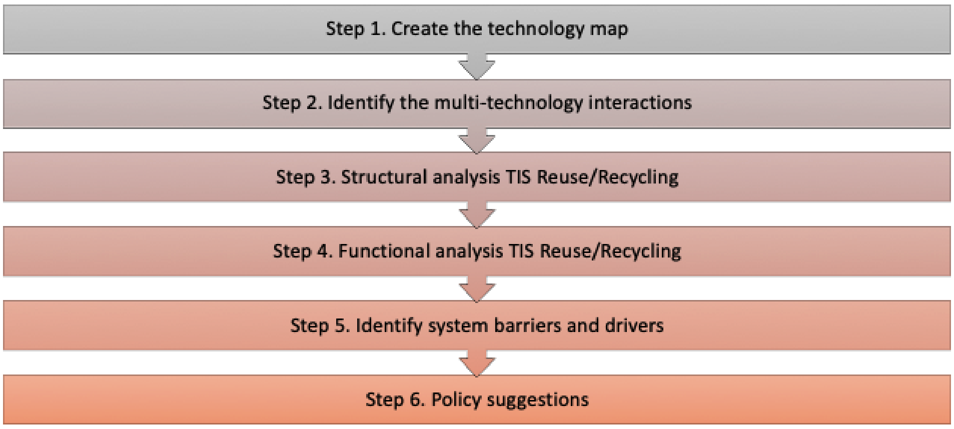
[5] The function(F7) of “Development of positive externalities” was omitted from analysis in order to reduce the complexity of the paper. Moreover, the function embeds in itself the dynamics of other functions that still will be discussed in section 5.4.

interactions. Third step includes the structural analysis of the Norwegian TIS of recycling and re-use. Fourth step includes the assessment of system functions with regard to multi-technology interactions in order to reveal drivers and barriers of TISs of recycling and re-use in Norway.

Figure 3.2: *Operationalization of conceptual framework*



3.3. Methods of data collection

3.3.1. Document analysis

The document analysis was conducted including several types of literature in order to gain understanding in several directions. First, the scientific articles and books on the LIB technological architecture were reviewed in order to gain an understanding of the components and sub-components of the given artifact, and to identify key terminology. This stage of analysis has provided an understanding of the role of each technology component in relation to the overall technology performance.

Secondly, the documentation on the Li-ion battery industry state-of-art and development was reviewed. The data included publicly available reports on market developments from related companies, consultancy agencies, and government official documents. The publicly available information on ongoing R&D projects was used to evaluate the industry formation in Norway, as well as identify relevant industry actors and knowledge organizations circulating in the field. The academic literature also included papers on Li-ion battery and other multi-component technologies analyzed by using various extensions of TIS approach. These papers helped to identify an appropriate analytical tool for the study. The academic literature within the field was retrieved through the data bases such as ScienceDirect, ResearchGate and Oria.

Finally, the analysis included documents on official public strategies and regulations in EU and Norway. The documentation on Norwegian industry, technology strategies, and regulations was retrieved from such websites as Government.no, Lovdata.no, and NVE.no, etc. This type of documents helped to identify current regulative environment in the country and reveal the existing regulative barriers for development of re-use and recycling in country.

3.3.2. Expert Interviews

By applying explorative interviews, the thesis provides a wider and more synchronous state of art representation than completely relying on written sources. The interviews were conducted with the experts in the field, appropriate stakeholders and policymakers in order to complement the primarily data. The interviews were in-depth and aimed to gather information on the expectations and opinions regarding technological development of the recycling and re-use in Norway, to detect dynamics within the industry and to unfold relevant actors´ experiences. The interviews were structured in advance in order to lead the conversation in a relevant for the research direction. However, the questions were open-ended so that participants were able to speak about particular aspects and concerns they find relevant. Hence, the interviews were semi-structured in order to be flexible with questions and topics for both me and participants (Yin, 2009).

The interview guide was constructed considering six functions suggested within the TIS literature (Chapter 2). The questions were modified according to the industrial sector, governmental body or knowledge institution a participant represents. The question guide can be found in the Appendix. The interviews were conducted face-to-face or via video conference software with duration ranged from 45 to 120 minutes. The interviews were recorded with the written permission of the informants. The audio-recorded interviews were subsequently transcribed and analyzed using qualitative data analysis software, NVivo.

In order to get a comprehensive overview of the emerging industries around recycling and second-life in Norway, the interviews were conducted with the industrial actors engaging in the formation of Li-ion battery recycling industry in Norway, and those who have already implemented the battery second-life projects. Eventually the interviewees included: 1) secondary materials suppliers and prospective recyclers; 2) waste management company; 3) second-life battery pack suppliers; 4) second-life battery system suppliers; 5) second-life battery users. Besides, the purpose was to collect information through the interviews with other stakeholders who are involved in the formation of the battery second-life innovation system in Norway, as for example with knowledge institutions and governmental bodies.

3.3.3. Direct observations

According to Yin (2009), observations provide additional information about the topic of interest, and help to understand the context or phenomenon in focus. Since an introduction of EV battery recycling and re-use in Norway is not a historical but rather the ongoing process, the visit of conferences was a relevant method of data collection. The first conference was held in June 2019 in Fredrikstad, Norway by European association of national collection schemes for batteries[6]. The second event is a politically independent forum where political leaders, business leaders, entrepreneurs, governmental organizations meet citizens in order to present and debate on social and publicly beneficial topics. The relevant for the thesis session called “How to secure circular use of resources before the battery wave takes us” which was held on 15.08.2019 in Arendal, Norway. This event was, however, observed thought the online platform. The objective was to understand the state of art within the industry from “inside” and to combine it with the “external” perception (Yin, 2009, p.112). In addition to that, the social-media such as Twitter and LinkedIn was used in order to follow recent developments of the technologies of the LIBs, recycling, and second-life. This method was also used to apprehend the market actors’ expectations and uncertainties regarding market, technology, and regulations.

3.4. Reliability & Validity

Reliability

Reliability demonstrates that data collection procedures applied in a given study will give the same outcomes if repeated in the analogous research (Yin, 2009, 40). One of the approaches how a study can be replicated is by following the documented procedures of the previous study (Yin, 2009, 45). Chapter 3 included the detailed rationale for focus of this study and the step-by-step procedures of the analysis performed in this thesis. It can be repeated by other researchers in the course of equivalent studies, however due to the highly dynamic industry development, over time the results among researchers may vary.

During the data collection all the interviews were recorded and transcribed. The questionnaire for interviews was made with regard to the six functions of the innovation processes. It can be found in the appendix attached to this study. The questionnaire, however, was periodically modified depending on the type of the company or organization a participant represented. For example, respondents involved in the recycling or re-use of Li-ion batteries were asked about

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[6] https://www.eucobat.eu

the changes in the market for appropriate for a participant technology. However, the questionnaire also included questions about an adjacent sector that might play a role in their particular technology / sector / market. The respondents within the government institutions were asked questions about regulation on both battery recycling and second-life batteries. Moreover, the presentations and audio and written notes from the conferences were saved. The collected data was saved in one place and organized in a manageable and consistent way enabling a straightforward access to the information. Further, the data was coded in compliance with the TIS functions and key processes influencing different sectors of the value chain. Each function was assessed by using common indicators, for example a function "entrepreneurial experimentation" was diagnosed by such characteristics: the scope and diversity of entrepreneurial experiments and demonstrations; development and implementation of different types of applications (for re-use) and processes (for recycling); the degree of complementarity with existing technologies, etc. In this manner, the reliability of the study has been strengthened.

Validity

In order to increase the validity of the research, the data was collected through multiple sources of evidence. This included to collect data from interviews and document analysis. The internal validity, which reflects the credibility of the conclusions made in the study (Yin, 2009, pp. 40-43), was achieved by comparing the results of the study with previous similar studies using TIS framework. The functional pattern of the TISs in Norway was compared to the functional pattern which prevails to emergence of new industries, and TISs. The external validity indicates whether a study´s outcome is generalizable outside of the given research (Yin, 2009, p. 43). The findings of this study might be not generable outside of the battery recycling and battery re-use in Norway.

3.5. Ethics

Qualitative research often involve invading someone´s privacy (Yin, 2009). This thesis used data which can be linked directly or indirectly to individual persons through combination of information, what makes this data private. Additionally, all the interviews were recorded. Therefore, the research project was registered at the Norwegian Centre for Research Data (NSD) and approved in June 2019. All the interviewees received personally or through an e-mail invitation form to participate in the study by means of an interview. The form included the information about the ongoing research, the responsible for the research organization

(University of Oslo), how an informant can refuse to participate in the study at any time and overall rights of the research contributor. The interviewees were informed that they will be anonymized in the thesis, however their positions in the specific companies or organizations will be revealed. The candidates were given time to read and sign up the form.

3.6. Research limitations

Some of the relevant to the study documents were restricted or had to be purchased due to the competitive markets of both recycling and second-life EV batteries. Such documents included research on market developments and market growth forecasts. Therefore, the research was based only on publicly available data. The research might have an observer bias due to the researcher's interpretation of the information collected during the interviews. Additionally, the interviews were conducted in Norwegian language and later translated into English. It implicates that the translation might have affected the original meaning and, therefore, the author´s interpretation of the events or activities. Therefore, in order to minimize the errors, the collected during the interviews data was verified by means of additional literature, research articles and publicly available documents. Moreover, if some details or single piece of information from the certain respondents was notably falling apart from the common pattern, it was excluded from the analysis in order to avoid the delusion.

4. Analysis of EV LIB technology chain as TIS context

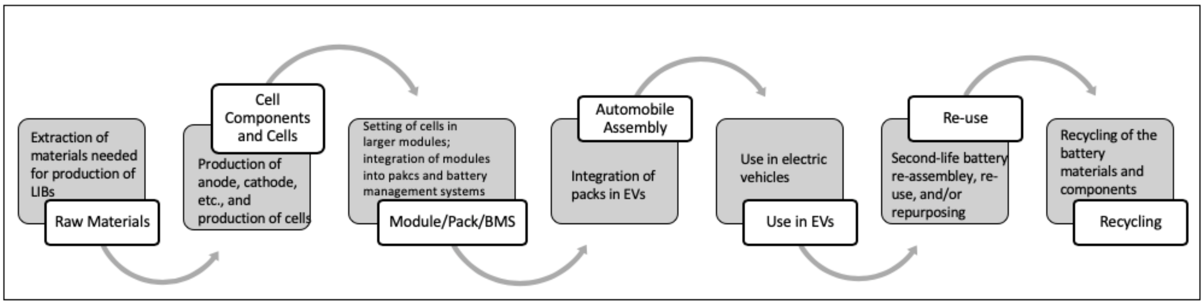
This chapter depicts the value chain of the LIBs including the production of the battery´s components, assembly of the battery packs, battery primary and secondary applications, as well as recycling processes. The value chain description will also provide a brief insight into the geographic distribution of battery production, use, and recycling in order to understand the international LIB market developments. The value chain narrative will be then used to identify the multi-technology interactions and specify the important context elements for TISs of re-use and recycling in Norway.

4.1. Lithium-ion Battery Architecture and Value Chain

Lithium-ion battery is a multi-component technology, i.e. it is composed of different technological components and sub-components which makes this technological artefact "a complex system consisting of hierarchy of sub-systems" (Murmann & Frenken, 2006). The production of all necessary elements included in LiB is carried out by different manufacturers representing various industries and different regions of the world (Stephan et.al, 2017). This entails that a fully operational Li-ion battery in the EVs pre-passes a long assembly process implying internationally segmented and geographically scattered production. The LIB´s architecture defines the upstream and downstream sectors and supplier-customer relations which are disclosed in the value chain (Stephan et.al, 2017).

In terms of this thesis, the value chain of lithium-ion battery for EVs is represented in seven segments: 1) raw materials mining; 2) cells and cell components manufacture; 3) pack/modules/systems manufacture; 4) EVs manufacture; 5) use in electric vehicles; 6) re-use; 6) recycling (Figure 4.1). Raw materials production, cell components and cells manufacturing relate to the upstream sectors; while manufacturing of packs, modules, and battery management systems along with the utilization of batteries in electric vehicles refer to the downstream sectors. Upstream and downstream sector are followed by re-use and recycling of materials.

Figure 4.1: *Lithium-ion battery value chain*



Upstream sectors

Li-ion battery is a natural material-based technology; therefore, the starting point of its value chain is the extraction of the raw metals. A battery contains such materials as natural and artificial graphite, copper (Cu), aluminium (Al), lithium (Li), cobalt (Co), nickel (Ni), and manganese (Mn), and silicon materials. The mining of the required materials is performed worldwide. However, major supply are usually concentrated in certain regions due to the favorable geological condition. Due to a set of material supply issues discussed in Introduction, the instability within the mining sector reflects on other segments of the value chain. For example, the scarcity of certain metals and minerals, induce the innovation and development within the chemical sector aimed to replace critical materials in the battery sub-component cathode.

The essential battery components are cells consisting of two electrodes (anode and cathode), electrolyte and separator. Dominant anode material among manufacturers is graphite, with additives of lithium titanate and silicon-based materials in some cases (Gaines, 2014; Mishra et al., 2018). Cathode is the most valuable component of the battery and is mainly composed of graphite, lithium (Li), cobalt (Co), nickel (Ni), and manganese (Mn) (Zubi, Dufo-López, Carvalho, & Pasaoglu, 2018a). Depending on the composition of the elements in cathode, commercial Li-ion batteries are currently represented in five main types: lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminium oxide (NCA), lithium manganese oxide (LMO), and lithium iron phosphate (LFP) (Miao, Hynan, von Jouanne, & Yokochi, 2019). The chemical composition of the active materials in cathode vary across manufactures and is under the constant change, therefore can hardly be standardized (Gaines, 2014; Lu, Rong, Hu, Li, & Chen, 2019). Each of the chemistries has its own characteristics and are different in performance, costs, safety, and a life span (Reid & Julve, 2016).

The anxiety about the cobalt supply origins encourages researchers on the design of advanced materials and battery manufacturers to experiment with the battery´s chemical anatomy in order to reduce the cobalt content in cathode for to overcome the dependence of the technology on this material. For example, an American automotive and energy producer Tesla declares in its annual impact report that the company uses nickel-cobalt aluminum oxide (NCA) battery cells, which is a high-nickel cathode with lower cobalt content (Tesla, 2018). Chinese battery and energy storage manufacturer Contemporary Amperex Technology (CATL) is another example. Despite other motives, one if which is the market competition with the Korean battery producers LG Chem, Panasonic and SK Innovation, the company has recently announced the intentions to start mass production of cell types NCM 811, which use 8-1-1 proportions of nickel, cobalt and magnesium respectively (Barrera, 2019).

Manufacture of cells sub-components is led by the Asian region and has been shared among China, Japan and South Korea. The market can be characterized as highly dynamic due to the harsh competition among players. European and the U.S. manufacturers have been showing an interest in the entering the field of production, however do not constitute a crucial part of the market share. The production of some of cathode active materials has also been performed by cell manufacturers individually because quality of cathode materials explicitly impacts the cells´ productivity (Lebedeva, N., Di Persio, F., Boon-Brett, 2017). The cell production itself in 2015 was dominated by China, Japan and Korea. From 2016 the global market share of the cell production has been changed because of the opening of a cell plant in the U.S. by automotive giant Tesla with the manufacturing capacity of 35 GWh (Chung, Elgqvist, &

Santhanagopalan, 2016). Depending on data resources and data collection methods the numbers on cell production in Europe vary. The estimates of production capacity is approximately 1.3 GWh per year, what corresponds to 5 per cent of the global production capacity for automotive applications (Lebedeva, Di Persio, Boon-Brett, 2017).

This segment of battery value chain is the most crucial for the technology and market actors. The significance of batteries for energy transitions both within transport and energy sectors magnetize companies to enter the race of cells production. The automotive industry is becoming a driver of growth for the production of battery cells in Europe. Stakeholders attract investments in order to become among the earliest on the European market, as for example Northvolt AB. The Swedish company is intended to build Gigafactory of battery cells production in Skellefteå, Sweden, additionally positioning itself as a battery systems manufacturer. According to the company´s website, the production capacity of the factory is estimated to be 16 GWh per year, and has already significant equity capital through the investments of such industry giants as BMW Group, Volkswagen Group, and a loan from The European Investment Bank[7].

Hence, the upstream segment of the LIB supply chain can be characterized by strong competitive advantage of the Asian region. The downstream segments of the supply chain imply battery packs and systems production and implementation of the batteries in the electric transport. These sectors are more geographically dispersed.

Downstream sectors

After the cells are being produced in chemical sector, they move to the next segment of battery production which is performed by the power electronics sector. Firstly, in order to achieve greater capacity and voltage, cells are assembled into modules. Each module may contain from one hundred to five thousand individual cells (Gaines, 2014). The modules are integrated into battery systems, i.e. packs, composed together with control and protection systems such as a battery management system (BMS), a cooling system, and a communication interface (Schönemann, 2017). The BMS is used to monitor and manage key functionality and performance aspects such as voltage, current, state of charge and temperature (Zubi et.al, 2018).

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[7] https://northvolt.com/production/

Battery packs are designed to meet the performance requirements and depend on the type of the cell (Pistoia, 2014, pp.127-150). The battery pack design and production of BMS are largely performed by the original equipment manufacturers (OEMs) of the electric vehicles. Most of the OEMs try to keep control and profit margins over the technological assembly and design of the packs and battery management systems, and therefore, choose to develop manufacture capacity themselves or outsource it to the local companies (Chung et al., 2016; Lebedeva, Di Persio, Boon-Brett, 2017). In terms of insourcing battery pack production by EVs manufacturers, the U.S. have the highest volumes, mainly due to the production schemes of Tesla. EU has approximately similar manufacture capacity to Japan and China (Lebedeva, Di Persio, Boon-Brett, 2017).

The next segment of the LiB value chain is the utilization of the batteries in electric vehicles. In respect to the largest BEV producers, China leads the market with 33 per cent of the market share. EU, Japan, and USA follow with 22 per cent, 21 per cent and 22 per cent respectively (Lebedeva, Di Persio, Boon-Brett, 2017). As it can be observed, this part of the value chain has been shared among several countries and regions worldwide. The future scenarios of EVs growth give reason to believe that the global EVs production will remain the geographic diversity.

Re-use

At the time a Li-ion battery reaches the end-of-life in its original application, i.e. in EV, it remains active materials equal to approximately 80 per cent of the total capacity and, therefore, can be remanufactured or repurposed (Bobba et al., 2018). The remanufacture strategy involves a quality analysis of the battery cells with subsequent replacement of damaged cells, reassembly of the battery and re-use of the batteries in the cars (Schneider, Kindlein, Souza, & Malfatti, 2009). While remanufacturing of the batteries implies its second use in EVs, repurposing conveys an idea of using batteries in alternative non-vehicle applications (DeRousseau, Gully, Taylor, Apelian, & Wang, 2017). The pre-treatment for the repurposing also includes the reconfiguring cells, testing and development of another management system where both hard- and software will meet the new purpose requirements (Foster, Isely, Standridge, & Hasan, 2014).

Depending on the technical condition of the batteries, their subsequent use may be redirected for re-manufacture or re-use in other applications. Battery as such is an electrochemical system which convert electric power to another form of energy for storage, and then reconvert to electricity when required (Zubi et.al, 2018). Traditionally, large-scale Pumped Hydro Storage Systems (PHS) have provided almost 99% of worldwide storage capacity (Melikoglu, 2017). However, diffusion of the renewable energy sources (RES) created demand on auxiliary small-scale and more flexible energy storage technologies. The Li-ion battery can provide around 14 services for four stakeholder groups: energy utility, off grid, commercial and industrial (C&I), residential (Reid, Julve, 2016).

The EVs producers, such as for example Volvo, initiate the re-use of the batteries in their cars for the second time in order to maximize battery utilization and minimize customer cost of ownership. Yet, it is worth to note that OEMs in the partnerships with such sectors as electricity or telecom introduce new business models and pilot projects worldwide. For instance, automotive producer Nissan in cooperation with power management company Eaton have implemented *xStorage Building system* encompassing 280 Nissan Leaf EOL batteries in order to efficiently store and distribute energy and to provide back-up power services at the entertainment and sport events venue in Amsterdam (Nissan Insider, 2019). Another example is the Chinese government-driven agreement between sixteen battery and automotive companies and an operator of telecom towers to implement retired batteries as a back-up power (Melin, 2019). Currently, new projects on the secondary applications of the LiB start to gain momentum and although the market is a subject to numerous uncertainties, it is expected that it will continue to grow rapidly (ibid.).

Recycling

The final destination of the Li-ion batteries is recycling. Recycling is a process of material recovery. The process involves the collection and reprocessing of materials from the surplus of manufacturing and materials from the products per se (Duflou et al., 2008, p. 584). Recycling technologies can be divided into two broad categories: physical and chemical based technologies. The physical processes include mechanical separation, thermal treatment, mechanochemical and dissolution processes. Chemical processes incorporate acid- and bio-leaching, solvent extraction, chemical precipitation, and electrochemical process (Pistoia, 2014, pp. 509-524). The most widely used approaches of lithium-ion batteries recycling are pyrometallurgy, hydrometallurgy and direct recycling. Pyrometallurgical metal-extraction from the spent Li-ion batteries involves a high-temperature smelting reduction which lead to the recovery of valuable materials in the form of alloys (Zheng et al., 2018). A hydrometallurgical process implies leaching and extraction. This process benefits over the pyrometallurgical process in terms of high extraction efficiency, low energy consumption, little hazardous gas emission, and low capital cost (Lv et al., 2018). Direct recycling separates different elements of the black mass (active material powder from shredding of cells) by physical processes (Gaines, 2018, p. 2).

Recycling of LIBs is a complex and cost-intensive process. The absence of standardization of the Li-ion batteries leads to a diverse range of cell chemistries and battery designs, what also reflects on a complexity of dismantling and pre-treatment of EV batteries (Gaines, 2018). These issues complicate recycling processes and create a barrier for its smooth diffusion. Several large-scale recyclers have developed their own recycling technics. For example, the Umicore Battery Recycling Process, developed by the self-titled company, is based on pyrometallurgical and hydrometallurgical processes without mechanical pre-treatment of battery cells. The process is one of the most advanced recycling processes for Li-ion batteries and allow to reach a high recovery rates for nickel, cobalt, and copper. However, Umicore process is not suitable for recycling of cobalt- and nickel- free batteries, and aluminium ends up as a low-value material for construction (Pistoia, Liaw, 2018, pp. 304-307).

At present lithium-ion battery recycling is based on the recycling processes of batteries from portable electronic devices and is performed by approximately 50 companies located in China (over 30 companies) followed by South Korea, Europe, Japan and North America (Lebedeva, Di Persio, Boon-Brett, 2017; Melin, 2019). The recyclers in China and South Korea are closely connected to the producers of cathodes and anodes. The recycling market in these countries is driven by profit, and therefore companies compete for the EOL batteries what reflects on its high price (Melin, 2019).

Unlike China and South Korea, recycling market in Europe is less developed and the recycling efficiency is lower due to the unprofitability of the process as a result of the low battery volumes. Another factor that contribute to the low financial gain of the battery recycling in Europe is the fact that instead of the finished products for battery material market recyclers sell chemical components which require additional processing before they can be used in the new battery production. Other countries such as U.S., Canada, South Korea attempt to enter the recycling market, but struggle due to the low battery volumes what partially conditioned by the current battery flow to China (ibid).

An important nexus between the utilization of the LiB in the EVs and their further management, either as a second life option or for recycling, is battery collection with subsequent sorting and dismantling. The collection schemes of the batteries vary in different countries. In European Union, under the Battery Directive, an OEM who place any type of battery on a market has a responsibility to arrange recycling channels. In practice, it is organized through the national collection schemes, which OEMs can enter individually or more commonly, collectively. The collective scheme is organized with the participation of a third-party company, the Producer Responsibility Organization (PRO), which provides the management of the batteries at their EOL by means of the fees paid by producers (Drabik & Rizos, 2018).

4.2. Multi-technology interaction processes and overall context

As showed the description of the value chain, LIB consists of several technological components produced in different sectors. Moreover, after the end of the service life in a vehicle, it becomes possible to re-use the LIB as a stationary energy storage and recycle it so that secondary materials can be used for production of new batteries or other products. In order to reveal the linkages along the value chain, two types of multi-technology interactions will be taken into consideration: technology interaction within the focal sector(s) (intra-sectoral interactions), and technology interaction between different sectors of battery production and application and recycling (inter-sectoral interactions). These interactions will be displayed on the technology map (Figure 4.2).

Inter-sectoral interactions

The innovation processes mentioned above are also reflected in inter-sectoral interactions. First, the innovation of the battery cells in the chemistry sector has an impact on the recycling processes. The growing EVs market drives the developments of battery cells, and substantial variation of the constituent materials of cathode. According to Pistoia (2018), this reflects on the method of recycling, which can be either aimed at processing all different types of LIBs in one process[8] or to be individually adapted to individual battery chemical composition. The latter facilitate higher quality recycling compared to more common processes. However, such processes require high knowledge about cell construction and chemistry, what can be gained only by the collaboration between recyclers and cell producers (Pistoia, 2018, p. 302-303).

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[8] “In these process routes, the battery cells enter a pyrometallurgical treatment with minimum or without mechanical pretreatment, followed by further treatment of the process outputs, i.e., alloy, slag, and flue dusts, mainly by hydrometallurgical processes to recover the individual metals” (Pistoia, p. 302).

Therefore, cooperation between the chemistry sector of cells manufacture and the waste sector of recycling can have a complementary effect on the latter.

The earlier mentioned complementary linkage between recycling and dismantling processes could be improved by the cooperation and alignment between pack manufacturers and recyclers. For example, the joint development of battery pack design standards could supposedly improve dismantling and subsequently costs of recycling. The same complementary effect will occur for battery re-use, namely the reduced costs of dismantling can improve the competitiveness of used Li-ion batteries.

There is also a wider context which drives the innovation across LIB value chain, generating thus “imbalances” for recycling industry and battery re-use. Firstly, the ongoing transition in transport sector, which echoes in the EVs fleet growth, creates a pressure on critical raw materials. Under the constraint of interruptions in the supply of metals, cell manufacturers experiment on new cathode chemical composition in order to reduce the amount of cobalt used in the technology. However, at the moment, recycling processes are aimed to recover economically attractive materials such as cobalt, and the rest of the materials as for example lithium are of secondary importance (Gaines, 2018; Zheng et.al., 2018). Therefore, the high cost of cobalt provides financial incentives for its recovery compared to other materials. This means that reduction of valuable materials in the battery cells will require recyclers to respond and develop processes with higher recycling rates for other materials. At the same time, the time lag between the novel cells are being produced and batteries´ entrance to the waste stream enable recyclers to react. Experts also note that *“the car industry is very conservative. So, if the new technology comes, they will wait and see how it is applied, so it will take several years to make a change”* (Interviewee 2). Nevertheless, the linkage between cells production and recycling can creates “imbalances” for battery value chain and affect recycling in particular. The same context of the EVs growth impel innovations and development of less expensive batteries with better performance, what, as mentioned earlier, would diminish the competitive advantage of the spent EV batteries in the electricity sector.

Intra-sectoral interactions

The intra-sectoral interactions occur due to interdependence of different technologies used to provide the same output within one sector. Technology interdependence can manifest itself in competition or complementarity (Andersen & Markard, 2017). Within the power sector second-life EV batteries, first of all, compete with other energy storage technologies. The stiff competition caused by the growing need in energy storage what drives the innovation in other technologies. Different energy storage technologies can be classified into mechanical, electromechanical, electrical, and chemical. Among the electromechanical energy storage only, Li-ion batteries face competition with flow batteries, nickel-based batteries, metal-air batteries, lead-acid batteries, sodium sulfur batteries and others (Gallo, Simões-Moreira, Costa, Santos, & Moutinho dos Santos, 2016). The technologies that can provide large-scale capacities include the mature Pumped-Storage Hydropower, as well as Compressed Air Energy Storage (CAES), Hydrogen, and also compete with LIBs (Akinyele & Rayudu, 2014). Each of these technologies undergoes innovations for to achieve higher energy density, improve life circle, overcome environmental issues and improve other technologic qualities in order to provide greater flexibility to the power grid (Gallo et al., 2016). This means that Li-ion batteries should response to these innovations in order to remain competitive with other technologies.

Except for the competition between various energy storage technologies, the second-life LIBs might also compete with new LIBs. An important factor in this competition is projected price difference between new and secondary batteries. The growing market of Li-ion batteries, both in terms of its use in EVs and stationary energy storage, impel the technologic development of the batteries which will reduce the costs on new batteries in future. To be more specific, a number of innovation activities in the chemistry sector are directed at the change of the critical materials in the cell components. The chemistry will change in pursuit to use more accessible and less expensive materials what in turn will result in the new LIB cost decline (Hesse et al., 2017, p. 2). In turn, the costs of spent EV batteries depend on several management stages which the battery has to go through including dismantling, security assessment, battery pack assembly, and transportation (Klör B., Beverungen D., Bräuer S., Plenter F., Monhof M., 2015). For the moment, the costs of the refurbishment process does not exceed the production cost of new batteries:

> *"The cell manufacturing in particular implies large expenditures involving several parties. We, in turn, have ready-made cells that simply need to be checked and transported. Therefore, the spent battery pack is less expensive than the new one, at least for our company"* (Interviewee 9).

However, systematic review studies showed the annual decline of the EV battery pack costs between 2007 and 2014, and the forthcoming price is forecasted to experience up to 50 per cent reduction (Reinhardt, Christodoulou, Gassó-Domingo, & Amante García, 2019, p. 439;

Zubi, Dufo-López, Carvalho, & Pasaoglu, 2018b, p. 303). This means that when the price for new battery packs will be reduced due to the technology advancements, the second-life batteries might lose its competitive advantage over the new LIBs.

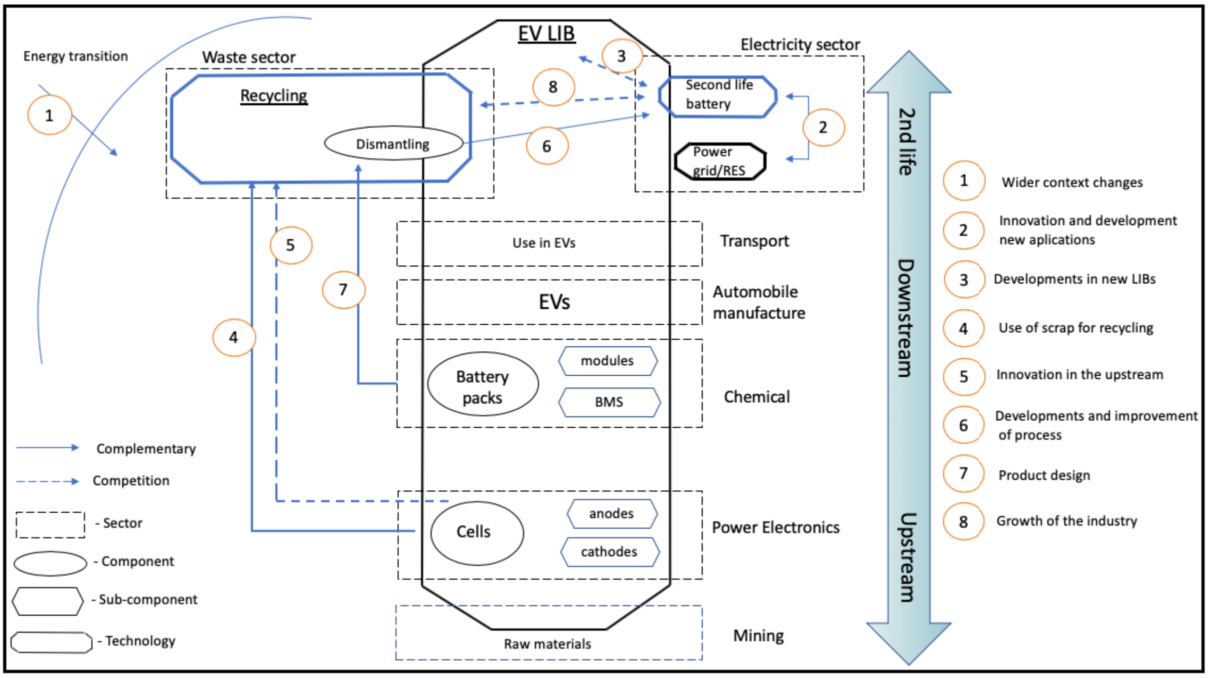
While competing with other energy storage technologies and new Li-ion batteries, the second-life EV batteries complement the technologies of renewable energy sources (such as solar and wind). The battery energy storage (BES) as such is considered to be a solution to balancing electricity demand and power supply under the large-scale integration of variable / non-dispatchable renewables into the power system (Hesse et al., 2017; Lehtola & Zahedi, 2019). It has been claimed that modern power network requires energy storage to improve efficiency and use of renewably generated energy (Gladwin et al., 2016). Moreover, energy storage is seen to be critical to the development of a smart grid (Ahmadi et al., 2014; Zubi et al., 2018b). Therefore, similar to stationary energy storage technologies, the second-life batteries can complement the RES and become a catalyst for the electricity sector transformation.

Within the waste sector, battery recycling is closely connected with the process of battery dismantling. Due to diversity of pack configuration and designs, the dismantling process is traditionally carried out manually and therefore can be cost inefficient in the countries with high labor cost (Duflou et.al., 2008). Battery packs may consist of several thousand cells grouped into stacks, i.e. modules. Additionally, battery pack include contractors, temperature and voltage sensors, BMS, system cover, etc., and each component increases complexity and dismantling costs. Moreover, removal of the battery pack from a vehicle is a time- and cost consuming due to a conflict of interest between the vehicle design in terms of crash security, space utilization, etc., and the preference of service-friendly installation position (Pistoia, 2018, p. 299-302; Wegener, 2014).

The complexity of the dismantling process increases the costs of battery recycling. Therefore, innovation and development of the dismantling process would have a complementary effect on recycling. Automatization of the disassembly could increase the efficiency compared to manual practices and facilitate recycling. At present, however, only partial automation is possible due to the variety of battery packs, a lack of standardization and unavailability of detailed battery designs for recycling companies (Herrmann, C., Kara, S., Kwade, A., Diekmann, J., p. 99-124). Referring to several research projects, Pistoia (2018) also suggests an installation of lifting points on battery packs to facilitate disassembly by use of standard lifting tools (p. 299).

To summarize, the technology mapping reveled the following multi-technology interactions along the value chain which have linkages with the focal TISs (Figure 4.2): 1) wider context changes including the strategies of countries to promote technologies of BEVs and RES, as well as interruptions in raw materials supply; 2) innovation and development of new applications and business models; 3) developments and innovations on the (new) Li-ion batteries; 4) use of the cell production scrap for recycling; 5) innovation in the upstream sector, which is reflected on the new chemistries for cells´ sub-components; 6) development and improvement of the battery dismantling; 7) Product design (standardization of products); 8) growth and development of battery recycling and/or re-use industries. Each of the innovation processes have either complementary or competitive interrelation with focal TISs. In some cases, both types are possible, as for example the interaction between recycling and cell production can bear the competition or complementary effect.

Figure 4.2. *Technology map*



5. Findings

This chapter presents the further analysis of battery recycling and re-use in Norway. The chapter contains the structural analysis of TISs of recycling and re-use, as well as functional analysis of these two TISs. The chapter concludes with identification of drivers and barriers for TIS recycling and re-use with regards to multi-technology interactions along the value chain.

5.1. Structural analysis

5.1.1. System actors

The focus of this thesis is the emergence of two TISs of re-use and recycling in Norway. The actors who participate in the formation of the innovation systems of recycling and re-use include commercial actors, governmental institutions, and knowledge institutions. Market actors who are active in the pre-development stage of the industry formation vary according to the sphere of interest. Therefore, the mapping of the market actors participating in recycling and re-use activities will be separated in two different sub-sections. Yet, it is important to bear in mind that some of the actors are interested in both recycling and re-use activities, as for example the intermediate companies such as battery collectors. The governmental and knowledge institutions are to a large extent coincide for both sectors. In connection to this, these two components of TISs will be discussed jointly. The mapping of the networks is also under the one section. This is so due to the fact that at the early stage of TISs development networks are formed under the R&D projects. There are some research projects which focus either on recycling or re-use, however most of them are about the technology of the Li-ion battery and covers the entire battery value chain.

5.1.1.1. Market actors

Market actors in battery re-use TIS

A variety of applications for second-life EV batteries creates market opportunities for heterogeneous actors from different sectors. Of paramount importance are those who own the batteries at the end of their life in an EV and decide on the next destination for the batteries, whether for recycling or re-use. In the Norwegian market, second-life EV batteries are provided either by car importers or by waste collection companies. The market of EVs is relatively new and most of the batteries are still in its first use and have not yet reached the end of its service life in the cars. Currently, automotive firm Nissan is the main supplier of spent batteries in the Norwegian market, although the batteries supplied by the company originate from outside of the country. The company cooperates with international power management firm Eaton which delivers electric components such as lightning controls, power distribution units, panel boards, sensors, etc. In the partnership with Nissan, the company ensures a quality and security assessment of the retired batteries Nissan Leaf, pack assembly, and transportation to the implementation place. These internationally well-established actors brought with them existing network, prior experience and capabilities favorable for emergence of the market for re-use of the EV batteries in Norway (Nissan Insider, 2019).

The second category of market actors who handles end-of-life batteries is the waste management companies. There are several waste collectors in Norway who specialize on the electronic and electric waste, however not all of them intend to collect EV batteries. The core competencies and experience is provided by BatteriRetur which functions as an intermediary between the transport and waste sectors. Established in 1993 the firm has competencies and approval in collecting all types of batteries, including the industrial high-energy batteries. Moreover, due to the hazardous risks, there are requirements for specific competencies in transportation and disassembly of the EVs batteries. The collection scheme for EVs batteries is planned to be carried out in the partnership with a non-profit collector company Autoretur AS. The firm was established by 26 Norwegian car importers and is responsible for collection and recycling of the cars in the country. The fundraiser is organized through three partners: Biljenvinning AS, Norsk Gjenvinning Metall AS and Bilretur AS[9].

The central market actors engaged with the development and installation of the EV second-life batteries, are the companies within the electricity sector, primarily RES suppliers and distribution system operators (DSOs). For example, such firms specializing in solar panels installation as Abmas AS, Kverneland Energy AS, and Alternative Energy AS are among the earliest entries to the innovation system of EV battery re-use. One of the first DSO to engage with second-life LIBs experimental installations is Lyse AS. Equally important market actors are the companies within IT sector, for example, Esmart Systems AS who develops software solutions for control of power lines, grid maintenance planning and energy flexibility optimization, and provides rationalization of energy through batteries and solar panels using artificial intelligence. Architecture companies are also starting to enter the innovation system of re-use, for example InCube AS and A38 AS, which currently work under the mutual project of developing zero-emission houses by installation of combination of solar panels and spent EV batteries[10].

It becomes evident that innovation system for re-use of the Li-ion batteries involves a range of diverse actors representing different sectors, such as transport, waste management,

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[9] https://autoretur.no/om-autoretur/

[10] https://www.enova.no/om-enova/om-organisasjonen/teknologiportefoljen/gjenbruk-av-elbil-batterier-som-energilager-i-bolig/

electronics, energy supply, IT, and construction. Each of the commercial firms entering this complex system brings unique knowledge, competencies, capital and other resources. Nevertheless, all actors perform within its own sector, and development and implementation of the second-life batteries is not a primary field of their activity.

Market actors in battery recycling TIS

Although the battery-recycling industry in Norway is not yet established, there are several actors who have intentions to construct the first pilot plant in the country. Since the establishment of the plant is a resource-intensive task, it requires prior knowledge and competencies which actors intend to acquire by creating a network of experts through the R&D projects. Currently, there are two active projects which cover the lithium-ion battery value creation in Norway. First innovation project “LIBRES” (Lithium-ion battery recycling) aims to develop an effective battery-recycling process with a high degree of material recovery, with further commercialization of the new process and establishment of the pilot battery-recycling plant in projected 2025[11]. The second project called “BATMAN” (Lithium-ion BATteries – Norwegian opportunities within sustainable end-of-life MANagement, re-use and new materials streams) works towards the development of a dynamic strategic tool based on material flow analysis (MFA) that will assist Norwegian companies to position themselves within the LiB value chain[12]. Both projects incorporate business actors, research organizations, and knowledge institutions which under the joint efforts are aimed to reach the project goals.

The industrial actors, whose participation in the aforementioned projects is justified by the intention to commercialize battery recycling in Norway, perform within the material production and processing industry. Norsk Hydro AS, which has a stable position in terms of aluminum production locally and at the international level, is a potential performer of the battery-recycling in Norway. Locally, Norsk Hydro operates aluminum plants in Sunndal, Høyanger, Årdal, Karmøy municipalities and Husnes with almost 1 million tonnes of primary aluminum production annually[13]. In attempts to expand its business horizons, the company has recognized commercial potential of the retired EV batteries and established a consortium for partnership between business and research communities in order to explore the upcoming technological and economic opportunities (Interviewee 1). The business model for Norway is

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[11] https://prosjektbanken.forskningsradet.no/#/project/NFR/282328

[12] https://prosjektbanken.forskningsradet.no/#/project/NFR/299334

[13] https://www.hydro.com/no-NO/om-hydro/hydro-worldwide/europe/norway/

yet to be developed and, due to the dynamics in the recycling field as a whole, still may be shaped in different ways. For the moment, the company's idea is to do both physical and chemical processing of the EV batteries to the level when the production materials will be of interest to other companies (Interviewee 1). Glencore Nikkelverk AS is the most potential partner in this case, which concurrently participates in the R&D projects "LIBRES" and "BATMAN".

Glencore Nikkelverk AS is a nickel refiner which also processes such valuable materials as cobalt and copper in a plant located in Kristiansand. The company with around 500 employees has an approximate production capacity of 92 000 tons of nickel, 39 000 tons of copper, and 5 000 tons of cobalt annually[14]. According to senior specialist (Interviewee 2), the company´s in-depth knowledge and extensive competencies in the field of material processing, gained over the years of operation, naturally led to the decision to become a part of the R&D project. After the projects are over, the company has an intention to participate in the pilot plant business model by acquiring valuable for the company materials from the EV batteries.

Another group of actors involved in the development of knowledge is closely related to the development of the anode and cathode materials. The participants include such companies as Fiven AS and Elkem AS. Notably, the latest has already invested in a pilot plant for battery graphite in Kristiansand, Norway[15]. The "LIBRES" project has also attracted finish mining company Keliber OY which specializes on the grade lithium hydroxide production with objectives to supply the international lithium battery market[16].

The aforementioned companies explicitly participate in the formation of the knowledge base around the materials production and recycling through the R&D projects. However, regarding the production and processing of materials embedded into the Li-ion battery chemistries, there are several firms present at the Norwegian market which could potentially be involved in the EV battery value chain. For instance, Alcoa is another corporation in the aluminum industry which has two smelting facilities in Lista and Mosjøen, with the capacity of 94 000 and 188 000 metric tonnes per year respectively. Skaland Graphite AS is a supplier of the graphite in Norway with 12 000 tonnes per year production volumes. According to company's

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[14] https://www.nikkelverk.no/no/OmOss/produksjon/Pages/produkter.aspx

[15] https://www.elkem.com/media/news-articles/elkem-to-establish-battery-graphite-pilot-plant-in-kristiansand-norway/

[16] https://www.keliber.fi/en/

research, the produced graphite can be used for the spherical graphite, which is a crucial component of the anode. Moreover, the Norwegian copper company Nussir ASA in 2019 has been approved by the government to start the copper mining in Kvalsund municipality, Finnmark. Notably, the company has applied for a financial grant in order to make the mining of copper firstly in the world completely electrified. The estimated time before the full production starts is from two to three years (Valmot, 2019a).

As can be observed, there are no actors in Norway who would commercially recycle Li-ion batteries yet. This one of the indicators that recycling TIS is in the formative phase of its development (Bergek, Jacobsson, Carlsson, et al., 2008; Markard, 2018). The incumbent companies within metal industry currently lead and initiate the R&D activities creating thus the first building block of the innovation system. Besides, engagement of the incumbents ensure the mobilization of financial resources to the projects. At the same time, all commercial entities are concerned about generating revenue from a recycling pilot plant, which means that without economic benefits, the construction of the plant may not go beyond the research stage.

Market actors along the value chain of the Li-ion batteries

Other segments of the LIB value chain include cells manufacturing and packs manufacturing, among which cell production is especially important for recycling market. At the time, there is a very small scale of the upstream sectors of the battery value chain present at the European market (Lebedeva, Di Persio, Boon-Brett, 2017). As revealed in section 4.1, the entire battery cell production is heavily concentrated in the Asian region and North America. Hence, such countries as China and U.S. have a competitive advantage and determine the dependence of Europe on the overseas manufacturers. However, realizing the advantages of establishing battery cell production in Europe and aiming to eliminate reliance on China there are several actors who attempt to enter the market, as for example Freyr AS.

Freyr AS is an industry player in Norway which has recently announced its ambitions to build a battery cell production facility with 32 GWh annual capacity in Mo i Rana municipality, Norway[17]. The project is planned to be implemented in partnership with SINTEF and NTNU, and has already received investment of 7, 25 million euro from a European investment company EIT InnoEnergy. Furthermore, the company´s scenario is to build a 600 MW on-

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[17] https://news.cision.com/freyr

shore wind energy farm in order to supply the facility with renewable energy, thus, making the battery cell production with close to zero GHG emissions. The objective of the company is to supply with battery cells the automotive, maritime, and electricity sectors in Europe and Norway. The opening of the plant is scheduled on 2023 (Valmot, 2019b).

Regarding the production of the battery packs, commonly, EV manufacturers make their own decisions about the battery pack design. For this reason, the production of battery packs is often located at the assembly points of EVs, and is carried out by the OEMs themselves or by local companies (Chung et al., 2016). Hence, it is rational that the production of battery packs in Norway is primarily concentrated within the niche marked producing modules for maritime sector. Such companies as Zem Energy, Corvus Energy, are representative examples within this segment. Additionally, Siemens has opened a partially robotized facility in Trondheim, producing battery packs for maritime sector (Stensvold, 2018).

The current and forecasted presence of the industrial actors from upstream sectors in Norway predetermines the favorable conditions for battery recycling and re-use. The disclosed multi-technology processes (section 4.2) along the value chain demonstrate the importance of inter-sectoral interactions and coordination between upstream and downstream sectors. The close geographical location of the market actors producing different (sub)components of the Li-ion battery technology will create stronger structural linkage. This aspect can lead to the TISs of recycling and re-use accelerated development.

5.1.1.2. Governmental Institutions

Government or public sector is entailed in TISs of battery recycling and re-use by different means given its various functionalities. At the national level, the government consist of ministries and public administrations which are responsible for policy and legislation development, setting the strategic directions of the country´s growth, collaboration with other public entities. The Norwegian Water resources and Energy Directorate (NVE) under the Ministry of Petroleum and Energy, has a function of management of Norway´s energy resources adhering the sustainable and environmentally responsible course. The Ministry of Climate and Environment affects all TISs participants through the development of climate policies, and the promotion and coordination of compliance with regulations and environmental standards at other sectoral levels. The Ministry of Transport and Communications has a proximate effect on the implementation and diffusion of the electric vehicles in the country since its responsibilities include the elaboration of law amendments, regulations, and strategies for the development of the transport sector, which are subsequently proposed for consideration to the Stortinget.

Aside from the designing of the normative regulations and development of the departmental strategies, the government carries out a financial support function. The central figure in the funding system is the Research Council of Norway (RCN) which first and foremost promotes research and innovation activities in the country. The entity allocates funds coming from 18 different ministries among the best applicants. Around NOK 10 billion are being invested yearly in the various R&I projects. The Council disburses funds among projects with high scientific quality that have impact within Norwegian industry and society, and create user-oriented outputs. In addition, RCN has a policy advisory role providing guidance to the authorities on the priority focus areas regarding R&D.

One of the RCN´s instruments is the *SkatteFUNN* program that helps firms of all sizes that seek to improve their products, services or production processes. A tax-intensive scheme supports businesses in a form of the tax deductions from 18 to 20 percent of the total costs of the projects in order to develop new technologies and propel innovations. Moreover, the companies within the *SkatteFUNN* program can apply through the Forskerpool (i.e. Research pool) system for involvement of researchers with relevant competencies to expertise their projects. In this way, RCN attempts to build a bridge between industry players and the scientific community.

The state´s financial assistance to businesses is also carried out through other governmental organizations. One of them is Enova, a state enterprise owned by the Ministry of Climate and Environment which provides financial incentives to the companies, entrepreneurs and private households. through appropriate targeted projects directed at the development of innovative solutions within energy and climate. The overall objectives of the Enova´s programmes is a promotion to the minimization of the green gas emissions and transition to the low-emission society. Regarding the Li-ion batteries, one of the Enova´s incentives is to support the electrification of the maritime sector by giving funds to the Norwegian ship owners for purchase and installation of the batteries. Moreover, the organization encourages householdings’ undertakings in implementation of the second life applications of the Li-ion batteries (Enova, 2019). Similar to Enova, Innovation Norway is a governmental funding organization which provides financial and advisory support to entrepreneurs and companies that alone with its development stimulate the economic, industrial and social growth within the regions (Innovasjon Norge, 2019).

5.1.1.3. Knowledge Institutions

Norway has a strong and influential scientific community within educational institutions and research organizations. The most of the large universities in Norway, such as University of Agder (UiA), University of Oslo (UiO), Norwegian University of Science and Technology (NTNU), carry out single studies on Li-ion batteries within its research area in the form of scientific articles, and master thesis papers. Additionally, several educational institutions are involved in the R&D projects on Li-ion battery chemistries, recycling, and business models development related to the batteries´ second life implementations. UiA and NTNU currently participate in the R&D project BATMAN which in collaboration with industrial representatives is aimed to explore the Norway´s opportunities within sustainable end-of-life battery management. These two universities also cooperate with industry actors on the R&D project LIBRES which explores the possibilities to develop and commercialize LiB recycling process with final objective to start a pilot recycling facility in Norway.

The projects also involve participation of the R&D organizations such as SINTEF (The Foundation for Industrial and Technical Research), Institute for Energy and Technology (IFE) and Institute for Transport Economics (TØI). An independent, non-for-profit research organisation SINTEF specializes on the applied research, technology and innovation in the multidisciplinary areas being a partner for private and public sectors. IFE is an independent research foundation which conducts research on energy, material technology, industrial environment, and other areas of socio-industrial relevance. The transport related studies are been carried out by TØI with a special emphasis on the implementation of the research outcomes within the industry. The institute follows the development in the EV volumes in Norway and makes a research on the lifetime of the cars on the market. Additionally, institution functions as an advisory board for public national and local authorities.

Non-profit company Smart Innovation Norway AS is another important innovation actor which conducts independent, applied research and specializes in research-based business development within smart energy and new technology. The company is a partner of the Norwegian-led project INVADE under the EU program Horisont 2020. The project´s objective is to explore how existing technologies such as batteries can improve the electrical infrastructure. It is based on a cloud-based flexibility management system integrated with

EVs and batteries, which allows energy storage to increase the share of renewable energy in an intelligent network[18].

Another type of knowledge resource is the consultancy agencies, which collect relevant data and provide statistical, analytical and advisory services. One of such organizations is Circular Energy Storage Research and Consulting, a London based agency which specializes on a lifecycle lithium-ion battery management. The firm regularly publishes subscription-available reports as well as it provides expert assistance to individual companies. Not to mention, the firm collaborates with public authorities, and participates in publicly available conferences. Particularly, in collaboration with The Swedish Energy Agency, The Circular Energy Storage has created a research report, an expert review over re-use and recycling of Li-ion batteries (Melin, 2019).

The presence of the research institutions and organizations in the country creates favorable environment within the innovation system for development and diffusion of knowledge among actors. The cooperation of the scientific community with industrials segments and public authorities contributes to the generation and transfer of knowledge as well as strengthen the capabilities of other actors.

5.1.2. Networks

The major role of the formal and informal networks is the knowledge and information exchange among actors, and mobilization of financial assets, as well as resources which have been developed over time such as trust among members, a common understanding of goals and reputation (Marko P. Hekkert & Negro, 2009; Musiolik, Markard, & Hekkert, 2012). As can be observed, the actors of the recycling and re-use TISs in Norway in order to build up a knowledge base within the field created formal networks under the R&D projects. The networks allow to establish connections between industrial players and scientific community, as well as to link industrial market players and intermediators.

In European Union there are numerous formal networks which gather key industrial stakeholders, interested EU countries, innovation and research, financial agencies, etc. One of the networks is a cooperative platform is the European Battery Alliance (EBA) with objective to create a competitive battery value chain in Europe with sustainable battery cells at its

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[18] https://h2020invade.eu

core[19]. Another example is association Eucobat which consists of non-profit organizations attempted to organize the collection and recycling of spent EV batteries[20]. In Norway, for battery recycling in re-use networks forms under the R&D projects. Informal networks are common for TIS reuse and generated in the professional fields, through participation in applied projects.

5.1.3. Regulative Institutions

In the European Union legislation regulates the waste batteries and accumulators under the *Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006*. The primary intention with the Directive is to diminish the negative impact of the (waste) batteries and accumulators on the environment in order to protect, preserve and improve its quality (Directive, 2006). In order to reach these objectives, the Directive restricts the placement on the market the batteries and accumulators that contain hazardous substances and stimulates collection and recycling of all types of batteries regardless weight, size, volume or material composition.[21] By introducing the extended producer responsibility (EPR)[22] policy approach, the Directive obliges producers of the batteries or the products containing the batteries to ensure the waste management of the batteries they put on the market. Wherein, the State Members authorities may provide the financing schemes for the battery waste treatment for OEMs operating in the national market. The directive sets the minimum recycling efficiency rate of 50 per cent of the average weight of "other waste" batteries and accumulations, the definition of which includes automotive lithium-ion batteries (Directive, 2006). To be more specific, this condition implies that 50 per cent of the weight of the battery must be recycled and does not require the recovery of individual materials such as for example cobalt or lithium (Drabik & Rizos, 2018).

According to the Norwegian legislation, anyone who professionally imports or manufactures batteries in the Norwegian market, including batteries embedded in other products, is considered to be a producer and is therefore responsible for the management of waste batteries. The producer must fulfill the producer responsibility through the membership in a producer responsibility organization (PRO), i.e. waste management company for discarded

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[19] https://ec.europa.eu/growth/industry/policy/european-battery-alliance_en

[20] https://www.eucobat.eu/about-us

[21] The lithium-ion batteries used in the EVs are not explicitly mentioned in the Directive but fall under the category of "industrial and automotive batteries" (Directive, 2006).

[22] Extended Producer responsibility (ERP) is a policy approach under which the producers are responsible to financially and/or physically manage the processing or disposal of products after consumption (OECD, 2019).

batteries approved by the Norwegian Environmental Agency (Avfallsforskriften, 2004). This means that when a vehicle is placed on the Norwegian market the car manufacturers are obligated to pay an environmental fee. Hereafter, the responsibility for a battery treatment shifts to a collector company and the fee covers the cost of collection, safe transportation, dismantling and recycling.

Similar to battery producers, an approved waste management company must follow the Norwegian Waste Regulations ("Avfallsforskriften") which comply with the requirements of the Battery Directive 2006/66/EC. While Battery Directive prevents the battery waste generation, it does not regulate the second-life batteries implementation. Therefore, market for re-use of batteries is unregulated.

5.2. Functional Analysis TIS Re-use

5.2.1. Knowledge Development and Diffusion (F1)

In 2019, the lithium-ion battery consultant Hans Eric Melin at the Circular Energy Storage company has published a publicly available report on the "State-of-the-art research in re-use and recycling of lithium-ion batteries" commissioned by the Swedish Energy Agency (Melin, 2019). According to the findings, 166 studies were identified as being related to the field of re-use of the LiBs. Most of the research originates from Germany, USA and U.K., where Sweden among those countries with the minimum research done. Three focus areas of studies have been distinguished: 1) technical possibilities and limitations; 2) economic potential; and, 3) environmental impacts (Melin, 2019).

Norway is not included on the list of countries which publish research on this topic, allegedly due to the low number of publications. Several interviewees have also admitted that a little knowledge development is happening through the scientific research or collaboration with knowledge institutions in Norway (Interviewees 6, 4). Nevertheless, some of the institutions are still involved in the international pilot projects, as for example NTNU participates in the EU applied research project INVADE under the research program Horizon 2020[23].

Experimentational and demonstrational projects is the major source of knowledge development among actors. An example is the international project INVADE which aims to implement a "smart system of renewable energy storage based on integrated EVs and

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[23] https://h2020invade.eu/

batteries to empower mobile, distributed and centralized energy storage in the distribution grid" (Invade, 2018). According to project´s statement, it will provide both the DSOs and the end-customers with information and enable them to exploit new opportunities arising in the EV battery domain (Invade, 2018). Another project "Re-use of electric car batteries as energy storage in housing" funded by Enova, uses patented method for reusing EV batteries as energy storage in homes and patented communication system for distributed energy storage[24]. By the end of the project the results will be published and disseminated to a wider community in order to spread the knowledge and to attract research institutions such as SINTEFF to collaborate and enhance the development of knowledge further.

One of the intentions with pilot projects, as can be observed, is to spread knowledge and experiences among users, DSOs, and educational and research community. The knowledge based on the pilot applications is also distributed among the professional informal networks. The test cases decrease the uncertainties about second-life batteries and, as an example, encourage others to promote and implement similar technologic solutions. An example can be Oslo municipality:

> "*Oslo municipality has a large real estate portfolio consisting of educational, social services and sports facilities. The electricity experts working with these buildings constitute an informal network of professionals who exchange with knowledge on different projects. So, we have a good collaboration on that side"* (Interviewee 6).

This example demonstrates that the experts receive tacit knowledge on applications of the second-life batteries and promote it to other actors. Therefore, knowledge is generated by experiential learning and diffused through the informal networks.

Stakeholders distinguish several directions in which the research and knowledge accumulation is required. Firstly, considering the spectrum of services that EV batteries can potentially provide (Section 4.1.), new business models need to be developed. Specifically, more research is required on how commercial cases can become cost-effective (Interviewees 6, 9, 10, 3). The knowledge about the life expectancy of the batteries during their first and second life, how the age affects the performance of the batteries, and battery degradation during its second-life applications could also contribute to the blooming of deployment

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[24] https://www.enova.no/om-enova/om-organisasjonen/teknologiportefoljen/gjenbruk-av-elbil-batterier-som-energilager-i-bolig/

scenarios. Moreover, there is also a lack of research on the evaluation of large-scale energy storage systems and improved battery pack monitoring and control (Melin, 2019).

The overall knowledge base in the country is insufficient and yet to be developed, what can be explained by the early stage of TIS development. The knowledge is generated mainly in the application-specific conditions, through applied R&D projects or financially supported pilot applications. The "learning-by-using" mode of gaining knowledge prevail in the condition of emerging re-use TIS. The user-producer interactions contribute to the learning based on the experiences of both sides. Therefore, the development of knowledge function is not a hampering factor for the TIS development at the moment.

However, the acceleration motor can be the development and exchange of knowledge in cooperation with the waste management sector (regarding the collection of batteries, and disassembly of battery packs), and power electronics sector (on battery packs and BMSs). Generation of knowledge about the lifecycle of a battery in its first application is also important for predicting when EV batteries will be available for second-life utilization in stationary purposes; how much capacity they remain; and how long they will serve (Martinez-Laserna et al., 2018).

5.2.2. Entrepreneurial experimentation (F2)

Due to the recent emergence of the concept of repurposing the EV Li-ion batteries and small amount of the end-of-life batteries on the market, experimentation on technology occur sporadically but vary from small-scale installations such as in mountain cabins[25] to large-scale projects such as at a stadium[26]. One of the reasons for experimentation is the willingness of public organizations to put into practice environmentally friendly technologic solutions. This disposition affects the direction of the search (F5) towards the use of spent LIBs. An illustrative example is a project which was initiated by Oslo municipality to apply spent Li-ion batteries from EVs at the Bislett stadium in Oslo. The officials has nominated a tender invitation for a contract on the application of spent batteries in conjunction with the photovoltaics (PV) installation at the local stadium. The tender included two major requirements: 1) an EV battery system should serve as an energy storage providing peak-shaving service; 2) a battery system supposed to operate as a back-up power (Interviewer 5).

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[25] NRK, https://www.nrk.no/telemark/brukte-elbilbatterier-gir-220-v-pa-hytta-1.14031967

[26] Klima Oslo, https://www.klimaoslo.no/2019/05/13/gamle-elbilbatterier-brukes-bislett-stadion/

In this way, both power peaks, energy costs and power grid load are reduced. The contract was won by electric company Ambas AS for which the installation of this type of battery system was the first experience. Moreover, the large-scale battery system which would function as a back-up power was implemented in the country for the first time. The development and installation of the system expanded the company´s competencies which it plans to use in other similar projects (Interviewee 4).

Experimentation also occurs through international research projects such as EU project INVADE performed by the power company Lyse AS. Under the direction of Smart Innovation Norway, the company installed spent EV batteries in twenty homes in Norway. One of the purposes with the project is to help smooth out the peak consumption spikes that occur when most of the power is used, such as on cold mornings or afternoons when homeowners come back from work. Another example of entrepreneurial activity is a project initiated by the architecture company InCube AS. Together with partners the firm aims to investigate the installation of the spent EV batteries as energy storage for the home with solar panels. Through the concept study the patented method for re-use of EV batteries as stationary energy storage in houses and patented communication system for distributed energy storage were developed[27].

The battery packs for two first mentioned projects were provided by electric international company Eaton in the partnership with automotive Nissan Leaf. However, several interviewees noted that the current barrier which hampers diffusion of experimental activities in the country is poor availability of the end-of-life batteries (Interviewees 4, 5, 6). Despite the fact that the volume of spent EV batteries is expected to grow in the forthcoming future, it still does not guarantee an access to the LIBs. This is largely due to the fact that the priority might be given to battery recycling prior to re-use of the batteries.

It has also been stated that there is a need to develop and implement various business models which would open the potential of the batteries providing different services: *"The possibilities can be enormous, and there is need to recognize them by introducing more pilot projects"* (Interviewees 6). Demonstrational projects would serve as representative cases and become a channel for knowledge spillover (F1). In turn, it will decrease the uncertainties regarding the second-life batteries and create the willingness among the newcomers to enter the TIS (F5).

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[27] Enova, https://www.enova.no/om-enova/om-organisasjonen/teknologiportefoljen/gjenbruk-av-elbil-batterier-som-energilager-i-bolig/

Though the participants admit that the financial support for performance of experimental projects is inevitable under present market conditions (Interviewee 6, 5).

There are also small firms which experiment, test and attempt to find solutions for the second life at the cell level of the batteries. For instance, Farco AS which specializes on products within mobile heat and electric energy, conducts testing and experiments with the cells which have mechanic difficulty to be re-used. The purpose is to make new modules and utilize them in the new battery packs with further applications in the mountain cabins and/or boats. The modules which have been created stay at the prototype level and are not commercialized (Interviewer 3).

Therefore, it can be noted that entrepreneurial experimentation on the second-life of the batteries is present in the country, and the number of pilot projects is growing. This indicates the growing investments and interest with battery energy storage. The experiments vary in terms of the different types of applications including the use of the batteries for such services as peak shaving control, back-up power, and energy arbitrage. The retired EV batteries have been used both for small entities such as maritime transport and private homes, and large utilities such as stadium. The experimentation also occurs due to the initiatives from the individual small firms, municipalities, and international projects. The factors retarding the diffusion of experimental activities are the access to the end-of-life EV batteries and high expenditures. The collaboration with automobile OEMs and third parties providing battery packs, and financial support is therefore required for the process to be accelerated.

5.2.3. Market Formation (F3)

For emerging TIS markets may not exist or to be underdeveloped (Bergek, Jacobsson, Carlsson, et al., 2008). In the case of TIS battery re-use in Norway, the market is at its “nursing” phase of development and can be characterized by a lack of the regulatory framework and small number or a lack of commercial implementation of the second-life batteries. Because of the early stage of the market formation, it is still unclear how the market will function regarding the ownership of the batteries by the end of its service in the EV. Klör (2015) has specified three possible forms of the market for second-life batteries based on existing market forms for trading automobile spare parts: 1) *closed market* – when the lifecycle of the EV battery might be completely covered by automotive and battery OEMs; 2) *intermediary-based market* – the intermediary companies might collect the batteries from car owners or automotive companies in order to provide them further for second-life applications;

and 3) *open market* – a marketplace operator might bring together supply and demand of used Li-ion batteries in conditions of the online marketplace (Klör, B.; Beverungen, D.; Bräuer, S.; Plenter, F.; and Monhof, M., 2015).

Proceeding from this idea, the Norwegian market is emerging the *intermediary-based* form. The market of EVs in the country is relatively immature, meaning that batteries at the end of its service in the car are not yet available. However, the spent batteries are present in other markets, such as the United States. Access to these batteries is provided by automotive OEM Nissan as their EVs were among the first in the mass market. Additionally, the provision of the battery packs to the customers implies not only the actual availability of the end-of-life batteries, but also disassembly of the battery to the cell level, cells´ assessment and replacement, re-assembly of the packs, and, finally, design of a battery system for repurposing. Therefore, a project of second-life battery installation requires collaboration among several stakeholders, namely, automobile OEMs who provides the batteries, a third party which offers the disassembly and re-assembly, and a third party which would set up a battery system that meets the requirements of a customer. However, the highly dynamic development of the market may still change the mechanisms of the second-life batteries allocation.

As showed in Section 4.2, Li-ion batteries have a large potential for utilization in a wide range of applications and delivering different services. The main area of application in Norway will be the use of LIB as an alternative to the expansion and reinforcement of power grids (2). Using batteries, the DSOs can postpone grid investments needed due to the proliferation of renewable energy. In combination with upcoming effect-based tariffs, the batteries will help end-customers to avoid high load in the periods when a tariff is high. However, since the DSOs have no right to own the batteries, there is still a question of its ownership which is a matter of regulatory framework. Therefore, this complementary interaction of the LIBs with power grid and RES technologies strengthen the LIBs legitimacy (F6) and influence the direction of search (F4) for DSOs and regulators. Yet, the complementary relations do not ensure the priority of second-life LIBs over the new EV batteries.

In the section 4.3. it was discussed that the second-life batteries will compete with the new batteries on the market (3). The costly battery pack disassembly and re-assembly can reduce the competitiveness of the second-life LIBs compared to the new batteries when the latter become cheaper due to the technology advances. Interviewed stakeholders see several solutions to this market constraint in Norway. Firstly, some of the interviewees highlight that dismantling performed at the domestic market will partially reduce the logistic expenditures and subsequently the second-life battery price. Currently, BatteriRetur operates dismantling plant in Sandefjord with capacity for several thousand batteries a year, and conducts a research on automatization and robotization in order to increase the capacity.[28] However, as was indicated earlier, some market actors experience insufficiency of *knowledge development* (F1) in this field, and highlight that there is a need for more research on battery dismantling. Secondly, dismantling process can be improved by cooperation with battery pack manufactures and standardization of the battery pack design (4). Although the technical difficulty lies in the fact that almost all automobile OEMs design battery packs differently depending on the car model.

At present, Norwegian market is characterized by the presence of pilot projects with positive outcomes, according to the interviewees. The current driver of market formation for re-use is the energy transition (1). This process concurrently drives the renewable energy market both in terms, expansion of the renewable energy resources and development of smart grid solutions. The favorable incentive schemes for PVs technology diffusion have equally positive effect on battery energy storage implementation, however, not specifically for second-life battery. Therefore, the direction of search (F5) could strengthen the willingness to utilize end-of-life EV batteries over the new ones. Moreover, an increase and diversification of demonstrations and entrepreneurial experimentation (F2) can reduce the uncertainties regarding the utilization economic and environmental outcomes and raise the expectancies about second-life LIBs. Furthermore, while innovation and rapid improvement (falling cost) of cell components makes new batteries more competitive with used batteries, strengthening knowledge development (F1) on battery dismantling in cooperation with battery pack manufacturers could improve the competitiveness of used batteries.

5.2.4. Resource Mobilization (F4)

Resources needed for the fundamental input to all activities within innovation system imply the financial capital in order to develop knowledge, physical infrastructure, skills and competencies, i.e. human capital, and complementary assets (Bergek et. al. 2008; Hekkert et. at. 2007). As mentioned previously, an important source of knowledge development for TIS battery re-use is applied R&D projects. Due to the high price of the battery packs, the pilot

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[28] https://www.eucobat.eu/sites/default/files/2019-06/10%20Fredrik%20Andresen%20-%20Batteriretur.pdf

projects require funding. As was discussed in section 5.1.1.2., Norway has sufficient government financial agencies for support of innovation projects. For example, the project of "Re-use of electric car batteries as energy storage in housing" received funding from Enova of NOK 366 000. Another example is the EU research and innovation project INVADE has a budget of €16 million distributed among five participating countries including Norway[29].

The commercial pilot projects also require economic assistance. As was highlighted by one of the interviewees (6), "*before this market start to grow it requires a financial support. The market will not have willingness to promote these kinds of solutions on its own".* The second-life batteries are not financially promoted by the government. Yet, there is a possibility to receive public funding. For example, project at Bislett stadium received a support of NOK 1 million from the Oslo's Climate and Energy Fund. The fund as such aims to stimulate energy savings and the transition to renewable energy. According to Interviewee 6, without this funding, the second-life LIB implementation would not have been possible.

When the second-life EV battery packs require substantial expenditures, it becomes important to understand the outcome of the battery installation. Therefore, there is a need to gain the knowledge (F1) on such aspects as for example the time when retired EV LIBs become available on the market, battery remained capacity, aging of the battery, evaluation of the costs versus benefits, etc. Currently, R&D project BatMan addresses these issues. The budget of the project is NOK 11, 75 million, which is a 50 per cent of the total cost. The other 50 per cent is financed by the companies that are part of the project.

The mobilization of resources also implies an access to human resources. It was already noted that in TIS re-use the knowledge is to a large extent generated through the experimental projects. Additionally, such projects help the companies to gain necessary competencies on battery system development and installations (Interviewee 6). This provides one more rationale for financial support of pilot projects.

The dismantling and reassembly of the battery packs are time-consuming procedures which requires skilled electro-technical competencies. As was mentioned previously, at present dismantling of the batteries is performed manually. Due to heavy weights and high voltages, the treatment of LIBs requires qualified personnel and specific tools (Pistoia, 2018 p.299). In Norway, a waste management company Batteriretur performs the above-mentioned

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[29] Invade, https://h2020invade.eu

procedures at its facilities in Sandefjord using specially designed analyzing equipment for the most common types of batteries. Besides, the company underlines that dismantling is performed by means of self-produced manuals, and the process is a continuous learning and knowledge cumulative process[30]. Moreover, the company provides training on handling of high voltage batteries to the partners and employees. To repeat, at least partial robotization of the dismantling process can reduce the demand on human resources (2).

The overall function of resource mobilization can be evaluated as strong. The public funding is available for R&D projects. The respondents do not perceive a human resource to be a constraint, however there is still a lack of competencies for development and installation of battery system with specific requirements. The required competencies, however, can be attained through participation in projects and ability to absorb the shared experiences of other actors at for example technology conferences or workshops.

5.2.5. Influence on the Direction of Search (F5)

Market actors must have sufficient incentives and/or pressure in order to enter a new technological field and to foster the formation and development of a new technology or industry (Bergek, Jacobsson, Carlsson, et al., 2008; M.P. Hekkert et al., 2007). The factors that influence the direction of search vary and can be articulated by industry, market tendencies and government strategies and regulations. Nevertheless, the guidance of the search is not totally defined by the market or government. As Hekkert et. al. (2007) note “it is often an interactive and cumulative process of exchanging ideas between technology producers, technology users, and many other actors, in which the technology itself is not a constant but a variable”. In this setting, actors´ expectations play an important role, especially during the formative phase of the TIS development.

The common narrative that influences the direction of the technological choices in the EU is a vision of the transition from linear the circular economy (European Commission, 2019). The strategy formulation and action plans open up opportunities for newcomers to start the experimental activities through the international programmes and projects, as for example INVADE, the project mentioned earlier. The circular economy strategy in Norway is not particularly formulated yet, however the concept as such is been addressed under the waste management regulation, which reflects the EU Battery Directive. As was specified earlier,

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[30] Eucobat, https://www.eucobat.eu/sites/default/files/2019-06/03%20Dag%20Albertsen%20-%20Batteriretur.pdf

under the waste regulation the battery producers must provide the channels for the battery recycling. This creates a pressure on automobile and battery OEMs to administer the batteries at the end of its service.

Despite the fact that the Battery Directive has an influence on battery producers it does not recognize the re-use of LIB as a solution to waste accumulation. EV batteries are classified as industrial batteries corresponding to "other" waste under the Battery Directive and are subject to recycling requirement. Therefore, the interviewed stakeholders agree that there is no institutional pressure to develop the battery second-life solutions.

Nevertheless, the institutional environment in the electricity sector impel the search for complementary technologies. In particular, the expansion of RES (e.g. PVs) directs the energy producers and consumers to search for technologies that can help adapt to regulations in the sector (2). For example, one of the NVE arrangements is the *Plus Accounts scheme* which brings in a concept of a *plus-customer* (NVE, 2019). The plus-customer, or a prosumer, is a customer who produces electricity for his own consumption and who delivers any surplus of production into the electricity grid. The surplus customer can feed maximum 100 kW into the grid. The benefit for plus-customer is of not paying a tariff for selling the surplus electricity to the customer's power supplier in accordance with NVE's regulations. Although the 100 kW limit is not an issue for typical households, for larger utilities such as schools, it might restrain the production capacity. Interviewees (6) exemplify:

> *"We have a school building at Holmlia which received a large number of solar panels. The installation was so large that it produced a lot of energy, so they had almost dump it somewhere. Since they could not feed more than 100 kW into the grid, the installation of batteries could have been a solution and serve as a back-up power"*

Another example can be an installation of battery energy storage as a response to electricity demand charge tariffs. In this case, the battery storage provides a peak load shaving, by storing energy during off-peak periods (when electricity prices are lowest), and discharging the stored energy during load peaks (when the prices are highest), reducing in this way demand charges for customers.

The institutional environment in the electricity sector influences, however, the direction of search for battery energy storage solutions in general, without providing specific motives to search for application of second-life batteries. This aspect also demonstrates the tight competition between new and the spent EV batteries (3). This implies that end-of-life EV batteries require more explicit influence on the direction of search in order to take its position on the market (F3).

One more factor which has an influence on search of new battery energy storage applications is the technology development in other countries. A supplier for second-life battery energy system for Bislett stadium project mentions:

> *"Right after we delivered the project, we went to the "Intersolar Europe", an exhibition for the solar industry and its partners, in Germany. We have realized that the battery energy system that we were developing for our project, could simply be bought as a finished product developed much earlier by other battery supplier"* (Interviewee 4).

This example demonstrates that Norwegian actors begin to observe a rapid development at the international markets in the field of energy storage technologies. Consequently, this can encourage local stakeholders to respond and direct their efforts towards finding new competitive solutions. The entrepreneurial experimentation (F2) at the Norwegian market has also an effect on other actors and induce them to expand the search for new solutions. The Interviewee (6) stated:

> *"We have partnered with a school building. They have had a so-called innovative procurement process where the use of the second-life batteries was one of the topics. So, we were actually faster than them to implement it".*

This example also shows how the knowledge diffusion (F1) among the informal networks influence the direction of search among actors. Moreover, the demonstrative second-life battery implementation projects reduce the uncertainties and increase the willingness to experiment in this field.

As mentioned in the beginning of this section, expectations also can influence the direction of search. Expectations among the actors about the future market vary. Some of the actors recognize a great potential with battery energy storage:

> *"Expectations are large. Specifically, in cases when the batteries are used as an emergency power the possibilities are enormous. For example, the second-life batteries can be used in the hospitals, police stations, data centers, and fire stations."* (Interviewee 5).

Others, while also recognizing the great potential of Li-ion batteries, still doubt about the future market for several reasons. Namely, the high cost of the batteries and the low price of electricity in Norway leads some to believe that the investment cost might exceed the outcome (Interviewee 6).

The function of influence the direction of search can be evaluated as moderate. There are almost no explicit guidance of search towards re-use of the second-life batteries. The waste regulative framework gives a direction towards recycling, and does not explicitly target the re-use of EV batteries. The institutional environment in the electricity sector creates favorable conditions to explore the battery energy storage solutions. However, it does not illuminate the second-life LIBs. Experimentations (F2) and knowledge diffusion (F1) effect on the influence the direction of search positively influence the direction of search function.

5.2.6. Creation of Legitimacy (F6)

Legitimacy formation is a socio-political process where expectations and visions are built through the actions of various organizations or individuals. Creation of legitimacy is of a great importance for emerging innovation system because it is required for actors to invest in new technology, to adopt it, to acquire the political strength, and for generation of demand (Bergek et.al, 2008). Achievement of legitimacy can induce resources (F4), create R&D incentives (F1), and form new markets (F3). In the early stage of TIS development, legitimation is mostly about make technology accepted as desirable and realistic (Bergek, Jacobsson, & Sandén, 2008).

Currently, there is no resistance to the re-use of Li-ion batteries. On the contrary, it has been recognized that re-use of the EV batteries is an environmentally friendly solution that adds value to the LIBs. Most importantly, the re-use of the end-of-life EV batteries contributes to the legitimation of electric vehicles. The opponents of electric cars argue about shortcomings in a battery production and the lack of solutions for post-vehicle battery disposal. The re-use of the LIBs, thus, weakens these arguments and advocates the EV adoption. Although there is no resistance to battery re-use, it still may appear from the OEMs of batteries due to the risk that second-life batteries may cannibalize the new battery storage systems.

The concept of reusing the EV battery is relatively new, and therefore skepticism regarding the technology performance may hinder the potential adopters from accepting the spent technology. Therefore, the functions of the knowledge development (F1) and entrepreneurial experimentation (F2) becomes very important in overcoming the technological uncertainties and contribute to legitimation. By applying the end-of-life batteries actors create a common vision about the technology which actually works in practice and brings the benefits to the user: *"Since the concept of using the second-life batteries is quite new it is important to show with such exploratory examples that it is possible to implement second-life batteries as solutions to energy production and consumption issues"* (Interviewee 5).

At the early stage of TIS re-use development the legitimacy function can be considered as weak. However, as Bergek et.al. (2008) highlight that legitimacy is not something given from the very beginning but "it is formed through conscious actions by various organizations and individuals in a dynamic process of *legitimation"* (Bergek, Jacobsson, Carlsson, et al., 2008, p. 417). The process of legitimation is related to institutional alignment. The proponents of the technology might either follow the rules of the existing institutional framework, or develop a new institutional framework (Bergek, Jacobsson, Carlsson, et al., 2008). This means that the advocates of the end-of-life battery re-use and policymakers are in the position when they can start to shape the favorable institutional environment for legitimacy creation.

5.3. Functional analysis TIS Recycling

5.3.1. Knowledge Development and Diffusion (F1)

In terms of global knowledge base, a total of 432 articles has been identified by Melin (2019), among which 59 per cent originates from China. The research on recycling can be divided into three categories: 1) recycling processes; production of materials from recycled batteries; and 3) pre-treatment processes (sorting, dismantling and discharging) (ibid.). The structural analysis has shown that in Norway a number of actors are in a process of gaining necessary knowledge in the field of LIB recycling before the pilot plant will be constructed. Knowledge is been accumulated around several aspects. On the technology side, the relevant actors consider to expand and improve the current recycling processes. The actors in metallurgy already acquire solid knowledge in processing of aluminium and refining of nickel and cobalt. However, the companies seek to improve processes in order to achieve high recycling rates. As stated by the expert, *"the one who will have the most efficient recycling process will have a priority on the market"* (Interviewee 1).

In addition to the accumulation of knowledge in the field of technological development of recycling processes, actors explore market conditions required for further establishment of the profitable business. An important question for actors is whether there is a possibility to create a profitable recycling industry for LIBs in terms of Norwegian market. The companies and organizations involved in the knowledge development conduct research with a purpose to understand the prospective market´s size, i.e. what volumes the batteries will end up on the secondary market and what quantity of batteries will be needed in order the recycling business to be commercially beneficial.

Stakeholders also point out at the lack of understanding of the entire value chain of the LIB, specifically on the material flow along the value chain. In particular, there is need to gain knowledge about potential volumes, timing and location where the Li-ion batteries will enter the waste stream (Interviewees 7, 3). The establishment of the recycling plant equipped with high technology machines is a capital-intensive process, which is why it is important for actors to recognize the proper time to build the plant and to ensure that the construction does not occur too early or not too late (Interviewee 7).

The knowledge diffusion largely occur through the common activities of actors and formal networks under the R&D projects. The networks also involve the international actors. However, the earlier established cooperation and formal networks make it difficult for newcomers to be involved in the knowledge development and exchange. Considerable part of knowledge base for management of recycling plants and recycling methods is also being acquired through China. According to interviewee (1), the company visits Chinese recyclers to derive knowledge on technological and operational attributes of the industry in the leading market. The knowledge also diffuses through participation in conferences, where commercial actors share their experiences of application of EV batteries, future expectations and strategies related to recycling processes, collection schemes, and dismantling activities.

The overall level of knowledge development and diffusion is sufficient for TIS further development. The more research is, however, required on battery dismantling practices. The ongoing research projects benefit from the involvement of various actors from the upstream sector. However, collaboration with EVs manufacturers, as well as producers of battery packs and systems could bring necessary knowledge and experienced for improvement of dismantling processes.

5.3.2. Entrepreneurial Experimentation (F2)

The experimentation on recycling processes is generally performed by well-established in the metal processing industry companies and medium-size firms. The companies innovate individually or by joint efforts with knowledge institutions through participation in research projects. As mentioned earlier, the performance on the market would depend on the most efficient processes implemented by recyclers. Therefore, actors try to gain highest recycling rates of valuable materials.

In the context of Norway, the incumbent companies within metallurgy experiment on the enhancement of the recycling processes in cooperation with local and international research organizations and scientific institutions. Within the scope of the LIBRES project, the experimentation activities are being performed by Elkem who has pilot capabilities for to perform the upscale tests from laboratory, especially high temperature processing (Interviewee 1). Additionally, an important participant for the project is the Institute for General Mechanics (IAM) at the RWTH Aachen University, Germany, which has a significant knowledge base and such equipment for experiments, tests and research as furnaces, converters, kilns, hydro-laboratory, etc. According to the interviewee (1), *"they have been working for many years on battery recycling including Li-ion battery recycling. So, they were by far the most knowledgeable group that we could naturally take on board".* Moreover, University of Agder, Norway, being a research partner for the project, operates Mechatronics Innovation Lab (MIL) for pilot testing and experimental development of products. The university conducts research on robotization and automatization with an intention to make a dismantling process of the EV battery pack automized (Interviewer 1).

Therefore, it can be noted that entrepreneur activities are being performed by incumbent actors who already have experience and competencies in materials processing. The companies attempt to expand their already existing practices and innovate on new recycling processes in order to obtain high recycling rates. The experimentation and testing is carried out in cooperation with several research organizations and institutions. However, it has been underlined that in case of already established collaboration between research communities and industry players, it becomes difficult for new actors to enter into such an alliance, since they can be a potential competitor to one of the participants (Interviewer 1).

5.3.3. Market Formation (F3)

In the European Union and Norway, the Battery Directive 2006/66/EC creates a market for battery recycling by requiring EV manufacturers to ensure recycling at least 50 per cent of the battery weight. Still, one of the current legislation weaknesses is the mandatory recycling rate of 50 per cent by the average weight of the battery. The low and not material specific requirement provides recyclers with an opportunity to prioritize the processing of valuable materials such as nickel and cobalt, and neglect cheaper materials such as lithium (Prior et al., 2013). Despite the fact that waste regulations make the OEMs responsible for securing the recycling of batteries placed on the market, it does not promote the local recycling industry, meaning that the batteries can simply be exported.

The market for recycled materials depends on the demand derived from manufacturers who would use secondary materials as a resource for production of new products. Commercial model for operational recycling plant in Norway is yet to be developed. However, the profitability of the operating recycling business will supposedly depend on the gate fee arrangement and a price of recycled materials. In turn, the price for secondary materials will be contingent on the costs of raw materials. The high price of virgin metals creates incentives for recycling. Conversely, lower raw material extraction expenses makes recycling cost-inefficient and the incentives for recycling diminish, as in a case with lithium. Moreover, ongoing research and development of the LIB technology is intended to use less expensive cathode materials. This will cause the aforementioned effect of reduced stimuli to recycle the EV batteries (3) (Wang et al., 2014).

For the recycling market the input variable, i.e. retired LIBs, plays a significant role. As mentioned earlier, at present the volumes of end-of-life LIBs are very low. A minor number of used batteries originates from the car accidents or failures in the battery systems. Current estimates and governmental transport strategy clearly indicate the upcoming EVs growth in the country. Nevertheless, remarkable rates of the electrification of the Norwegian transportation sector still do not ensure the sufficient supply of the batteries for to run a profitable business. Interviewer 1 stated: *"We have looked at the volumes that will be available and we see that in Norway alone it will be a fairly large market. Yet, it is not enough to really support this business".* The potential recyclers recognize, for the moment, several solutions to this market constrain. The first assumption is to increase the supply of the LIBs for recycling through the international market: "*Our thinking is that we should source at least from the Nordics or Europe, so initiative is to move beyond Norway"* (Interviewer 1). Secondly, the processing of the side materials from the cell production, may additionally offset the recycling costs (2):

> *"Production of cells involves a creation of scrap. A recycler who has an access to battery manufacturing scrap will have a cost advantage. In turn, a cell producer will need a recycler to manage scrap. European recycling costs will likely drop with production scrap from European cell producers"* (Interviewer 1).

The EV LIB value chain discussed in section 4.2, shows that at present, the cell production is primarily concentrated in Asian region and U.S. with increasing incentives from the European actors. Such distribution would make it difficult for Norwegian recyclers to rely on the scrap material. However, as showed the structural analysis (Section 5.1), Norwegian and Swedish actors are actively engaged in establishing cell production in the Nordic region. Thus, these prerequisites make it possible to assume that recyclers in Norway may have an easier access to the battery production scrap.

5.3.4. Resource Mobilization (F4)

As the lithium-ion battery recycling industry in Norway is at its infancy stage, financial resources are directed towards creating the knowledge base necessary to establish the first pilot plant in the country. The interviewed potential recyclers evaluate the allocation of the resources to be sufficient for the generation of knowledge. The expenses on currently ongoing two relevant R&D projects are partially covered by Norwegian Research Council with the budget of NOK 11,8 million and NOK 6,6 million. Remaining expenditure is borne by the commercial partners of the projects.

According to the respondents, a physical infrastructure cannot be built prematurely due to the high costs required for construction of recycling plant and its maintenance. Moreover, the market of end-of-life batteries exists but with insufficient volumes for the operating industrial unit. Therefore, at this stage of TIS development, commercial partners do not perceive the financial resources as a hampering factor. However, they acknowledge that the recycling business would require continuous investments because of the need to optimize processes to meet the changing chemical composition of cell components:

> *"It is difficult to make substantial investments in 20-30 years perspective, because you don't know what will be there in let's say 7 years. So, it can limit your willingness to optimize everything to be a super refiner"* (Interviewee 1).

An inevitable role for the constant input flow for recyclers play the collection of the LIBs. Although the EU and Norwegian legislation impose responsibility on EVs producers and provide collection national schemes, there are still uncontrolled gaps for battery leakages as for example export of the EVs or second life batteries. Additionally, the so-called "orphan batteries" may appear outside of the collection system in case the producer is no longer on the market due to for example bankruptcy, or ended activity on the local market. While this problem can possibly be solved with insurance schemes, one more issue for battery collection, and as a consequence for recycling market in Norway, is the intention of the OEMs to return the batteries (Interviewee 10). Such a strategic initiative may be conditioned by the rising value of the Li-ion battery, especially due to the extension of its service life through the alternative applications. Nevertheless, the actors are confident in the Norwegian battery collection scheme, and consider it to be one of the best in Europe.

The respondents do not perceive mobilization of human resources as a constraint. The pilot recycling plant can be built in the industrial park, close to other similar facilities. This will let the actors to get an access to professional labor (Interviewee 2).

Therefore, at this stage of TIS development, participants evaluate the resource mobilization function to be strong, and do not perceive it as a barrier for TIS development. The R&D projects enable the access to public funding. Moreover, formation of the projects helped to gather knowledge institutions, research organizations and business actors, among which the latter provide the financial support.

5.3.5. Influence on the Direction of Search (F5)

The promotion of the circular economy activities including waste management and management of raw materials at the EU level provides a generic direction for innovation and research activities for recycling industry as well as throughout the value chain of the batteries. For example, a *Strategic Action Plan on Batteries* adopted by European Commission in 2018 introduced a set of measures for R&I, financing, regulations, trade and skills development with the purpose to “make Europe a global leader in sustainable battery production and use, in the context of the circular economy” *(SAP, 2018)*. Among a number of goals, the Strategic Action Plan intends to secure access to the secondary raw materials through recycling, support European battery cell manufacturing in Europe, and accelerate deployment and industrialization of innovations along the value chain of the batteries (ibid).

Another example is a *Strategic Implementation Plan for the European Innovation Partnership on Raw Materials* (2013) which intends to boost the innovation capacity of the EU raw materials sector in order to secure the raw material supply where recycling is considered to be a part of the solution (SIP, 2013). The European Commission expects to encourage innovation activities within three areas: 1) raw materials research and innovation coordination; 2) technologies for primary and secondary raw materials production; 3) substitution of raw materials. The implementation actions include the substitution of critical and scarce raw materials in at least three applications; the search for technological solutions for the recycling the valuable raw materials from complex consumer products; and, the optimization of the collection of end-of-life products (ibid.).

These and a number of other measures at the EU level indicate that the policymakers attempt to strengthen the research efforts by guiding the search of new knowledge across the value chain of the Li-ion batteries. Moreover, purposeful targets promote the cooperation between knowledge institutions and industrial actors, as well as increase the incentives through the financial support. An overall effect of the strategic intentions of policymakers is the growth of positive expectations, which in turn motivate organizations and companies to develop and implement novel technologies in different sectors of the battery value chain.

Concerning the laws and regulations, the section 5.1.3 demonstrates that the EU Battery Directive regulates the battery waste in Europe. Additionally, the Battery Directive attempts to stimulate innovation and development of the efficient and eco-friendly recycling processes. However, the regulations do not explicitly support the implementation of these processes (European Commission, 2019). Similarly, the Battery Directive does not promote recovery of individual important materials such as for example lithium. Several interviewers have also argued that the Battery Directive (and accordingly the Norwegian Waste Regulations) has low requirements regarding the recycling rates which is the 50 per cent of the average battery weight, whilst the technological change enabled recyclers to achieve higher material recovery efficiency. It means that regulations do not create a pressure on the companies to develop and implement more efficient recycling methods.

Regarding the influence on the direction of search in terms of the Norwegian context, the interviewees underline two major factors influenced the decision to start the research on the recycling of EV batteries. Firstly, the experience and competencies of companies in the field of metal processing partially coincide with the knowledge necessary for recycling industry. The second factor is the significant size of the fleet of EVs in Norway, which will provide access to the batteries in the local market. Given this aspect, the expectations of EVs market growth (1), influence the direction of search for relevant companies to explore the possibilities to start a recycling plant.

Ancillary reason for stakeholders to enter the industry is the global market of the cell production and recycling and the dominance of China in this context which European actors try to avoid. Interviewee 2 stated:

> "*We have customers that say that "we want to have all our products, all our supply to be independent from China whatsoever". They don't want any contact. Those customers are not governmental, they are just professional customers that want to be independent. So those exist also".*

The concentration of the upstream sectors in Asian region and willingness of the European actors to avoid the battery production dependency, create incentives to establish the battery cell manufacturing in Europe. These intentions, in turn, influence the direction of search for companies to start the battery recycling industry. However, the interviewees highlight that the growing interest implicates higher competition. Therefore, in order to avoid the fierce rivalry, the companies must enter the industry considering the proper timing.

The function of the influence of search can be evaluated as moderate. At the wider context the energy transition and transition to circular economy create a guidance of search for recycling. The regulative institutions in the form of the Battery Directive and Norwegian Waste regulations create pressure to recycle the LIBs. At the same time, the legislation does not facilitate local battery recycling. The intentions of European and Norwegian actors to establish a battery production in Europe independent from Asian dominance also creates positive expectations among stakeholders.

5.3.6. Creation of legitimacy (F6)

Similar to re-use of the spent EV batteries, there is currently no opposition to the battery recycling plant in Norway. Since recycling is positioned as a solution to the generation of the waste batteries, its legitimacy can already be evaluated as moderate. Moreover, the environmental benefits from battery recycling coincide with the value base in the society. Moreover, legitimacy for recycling is getting even stronger considering that recycling contribute to the legitimation of EVs. Battery recycling have been also discussed by the public authorities as for example in the proposal from Parliament (Stortinget) to the government on more sustainable consumption and "Urban mining" (Stortinget, 2018). The recommendation suggests to submit a parliamentary report on Urban Mining[31], which

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[31] "Urban mining" means landfills, abandoned cables, etc. excavated to utilize the metal.

examines the potential for increased recycling of metals in Norway, and proposes measures to recover minerals and metals that are not in use.

At the moment, market actors admit an insufficient regulative framework and weaknesses of the Battery Directive. They express the need to increase the recycling rates requirements determined by the Battery Directive, and subsequently, Norwegian Waste Regulations. The waste collector companies express the similar concern on the collection rates. Therefore, the actors attempt to influence the legislation improvement in favor of recycling.

5.4. Identification of drivers and barriers

This section addresses the first research sub-question which is:

What are the main drivers and barriers for the EV battery recycling and re-use?

The system functions will be interpreted in order to understand the processes that influence the build-up of the TIS. The multi-technology interaction patterns reveled in section 4.3 will help to reveal how the TIS function have been influenced by these processes. The structural and functional analysis of battery recycling and re-use TISs reveals several major drivers and barriers of the TISs emergence.

5.4.1. Re-use TIS

The empirical findings show that TIS for re-use can be characterized as being in a formative stage of development. This is due to the presence of applied R&D and pilot projects, a small number of actors and high market and technology uncertainties. At this phase of TIS development entrepreneurial experimentations (F2) are especially important. The pilot projects in the country vary in terms of size and types of applications, however the number of them is still low. One pilot project is a large-scale second-life battery system installation at the local stadium. Other projects are aimed to provide services for small and medium households. The demonstration projects serve as a source of tacit knowledge development (F1) and as a method of gaining necessary competencies among actors (F4). Moreover, such projects reduce the uncertainties and increase the willingness (F5) of other actors to enter the TIS. The major driver for the entrepreneurial experimentation is the expansion of the RES technologies which occur due to the energy transition (1). The end-of-life LIBs can become a complementary linkage aiding the integration of RES into energy power system (2). The feature of the LIBs to provide complementary services also influences the direction of search

(F5) for this type of solution. Consequently, the increase of the RES volumes in the country is a driver for end-of-life LIBs adoption.

At present, experimentation is not feasible without public funding due to the high second-life battery costs. At this stage of TIS development, the financial resource mobilization (F4) is evaluated as to be moderate. According to respondents, the function does not create a constraint. The financial agencies provide necessary support to the R&D projects aimed at development and implementation of environmentally friendly technologies promoting efficient production and consumption of energy. However, the government does not provide explicit economic incentives to use second-life LIBs. The provision of fiscal incentives to promote spent batteries becomes especially important in the context of the forthcoming competition with the new EV batteries (3). The competition will mainly be caused by the price difference between the new and retired technology. Therefore, actors need economic incentives for to prefer the end-of-life batteries but not the new LIBs. The introduction of for example subsidies or tax credits will also attract the newcomers (F5) and increase the number of demonstrations and entrepreneurial experimentation (F2). In order to become more competitive, the costs on dismantling of the end-of-life LIBs could also be reduced (6). This can be achieved through close cooperation with battery pack producers (7) or partial automatization of dismantling process.

The market for battery re-use (F3) is underdeveloped and unregulated, what is a common feature of the TIS formative phase of development (Bergek, Jacobsson, Carlsson, et al., 2008; Markard, 2018). The major factor hampering the market formation (F3) is the poor availability of retired batteries. Moreover, the lack of information on battery performance in the first life, post-vehicle battery remaining capacity, the timing when the retired batteries will enter the market, make it more complicated for actors to establish a business model (F5). More knowledge about how to trace battery performance through its life is needed (F1).

This might, however, change when the batteries start to enter the waste stream. After end of service life in EV, LIBs enters the waste stream which is regulated by the EU Battery Directive, and Norwegian waste regulation. The legislation requires from EV manufactures to bear responsibility for battery recycling. However, Battery Directive does not specifically require producers to re-use the second-life batteries. This fact creates a vision that government prioritize the recycling. This causes the conditions of competition between recycling and re-use TISs (8). Stakeholders highlight that there is a need to develop regulative framework regarding the energy storage and end-of-life EV batteries in particular. A lack of clear vision or clear strategy to promote end-of-life EV batteries and unregulated market negatively affect the direction of search function (F5).

The lack of regulations and political visions on the re-use development in Norway also affects the legitimacy creation (F6). Although the re-use of Li-ion batteries contributes to the legitimation of EVs, the legitimacy for re-use of batteries as such is still weak. Additionally, the application of spent batteries can possibly meet the resistance from the battery producers under the threat that second-life batteries may cannibalize the market of new battery systems (8). Another hampering factor for legitimation process is actors´ skepticism concerning second-life batteries performance in new applications and economic benefits of its implementation. More information on technology issues (F1) and increased number of demonstration projects might help to overcome the barrier.

To summarize, it can be observed that TIS reuse is at the early phase of development. The immature market, not articulated demand, and high level of uncertainties require the governmental interference and proactive strategies. The cooperation between actors and supplier-user interaction establish in the conditions of market formation (Bergek, 2008). Therefore, there is need to identify new niches for second-life batteries and stimulate them in order to create a place for experimentation and consolidation of this technology. Almost all functions are relatively weak, and low number of actors. The key drivers and barriers of the system can be found in Appendix.

5.4.2. Recycling TIS

Meanwhile, TIS for recycling is at a very early stage of development and there no pilot recycling plant in the country. Currently, actors who promote battery recycling in Norway are focused on research and development (F1), and building networks between industry, knowledge and scientific communities. The ongoing two major R&D projects function as an umbrella for actors under which they can experiment (F2), exchange with knowledge and competencies (F4). Hence, the projects function as a common learning platform for stakeholders. Moreover, participation in the projects gives an access to the physical infrastructure (e.g. labs) (F4) for testing, experimentation, and development of battery cathode and anode materials, and recycling processes (F2). The structural analysis showed that the networks are formed by the incumbent actors which are indented to expand their traditional business and research activities. Their participation in the projects also ensures the attraction of financial resources necessary for research activities (F4), both the public funds and contributions of commercial partners.

As mentioned above, actors develop knowledge (F1) and experiment (F2) on battery materials, focusing thus on the upstream sector of the battery value chain. Moreover, the changes in the cells sub-components influence the direction of search (F5) for new recycling processes (5). Therefore, actors conduct experiments (F2) in order to achieve the higher recycling rates and develop cost-effective recycling process.

The major driver for emerging recycling in Norway is the expectations (F5) on the growing EVs market under the energy transition and governments intentions to decarbonize the road transport (1). The government´s explicit strategy and promotion of EVs, in addition to well-established collection schemes and Waste regulations, ensure for potential recyclers an access to a large number of batteries. Nevertheless, for actors there is still an uncertainty on whether these volumes of LIBs will be sufficient for economically viable business. Another doubtable question is whether there is a sufficient infrastructure capacity for dismantling of large volumes of retired batteries. These and a range of other questions regarding the future volumes of the EV Li-ion batteries require development and generation of knowledge on these aspects (F1).

Further, the EU countries seek to weaken the battery cell dependency on Asia, and have ambitious plans to establish a battery cell production in Europe, including Norway. This aspect creates positive expectations among potential recyclers (F5) as it will give better access to the cell production scrap (4) what in turn may reduce the recycling costs (F4). Cell producers will also become potential customers for secondary materials (F3). At the same time, the development of the second-life battery applications and its diffusion create uncertainties for potential recyclers (8). The better knowledge on second-life battery market and actual material flow (F1) on the market are needed in order to overcome the market concerns.

The market for battery recycling (F3) is created by the EU Battery Directive and specular Norwegian Waste Regulation by introducing the EPR, i.e. the responsibility of EVs manufacturers to secure the recycling of the minimum 50 per cent of the battery weight. The current barrier for market to develop is the low volumes of spent batteries on the market (F3). The barrier for recycling market is the volatile prices on raw materials and improvement of battery cells (5). Under the energy transition (1), the EV fleet growth induces innovation on the cell components with an objective to decrease the high prices on battery packs, and consequently EVs. Additionally, the environmental and social hazards of the critical materials extraction (as for example cobalt), are another factor that puts the pressure on the cell production. As a result, the cells developers aim to decrease critical materials in the batteries. The reduction of the economically viable metals from the battery chemical configuration lessen the incentives for battery the recycling. Therefore, there is a need for protective environment for battery recycling market formation (F3).

Due to the fact that recycling is a solution to waste generation and raw materials scarcity, the legitimacy is already moderate even though the TIS is at the very beginning of its formation (F6). Moreover, the recycling can contribute to the legitimization of the EVs adoption. The battery recycling is also a common topic on the political agenda, especially in terms of strategy to move from linear to circular economy. At the same time the requirements for recycling rates are considered to be low, and actors expect legislation to be improved.

The TIS recycling, same as re-use, is at the formation phase of development. Although the main constraint for TIS recycling development is the low volumes of spent batteries, the system has a range of other barriers. Several hampering factors are related to the innovations in the upstream of the value chain. At the same time, the interest of large companies in the establishment of the industry create favorable conditions for TIS to develop knowledge base and attract financial capital. The knowledge development is currently essential factor in emergence of battery recycling industry in Norway. Research on economic, technical and regulation aspects will determine whether the first pilot plant will be built and recycling TIS will continue to develop. Yet, there are still a great number of concerns which can lead to the TIS stagnation because of the lack of knowledge and confidence in the future market, strong international competition, or incapacity to adapt to the innovation process along the value chain of the batteries. In the Appendix the current and prospect system drivers and barriers are presented.

6. Discussion and Policy Suggestions

In order to answer the main research question, the following sub-question was asked:

How can public policy stimulate new industry formation in these areas?

The structural and functional analysis have helped to reveal system drivers and barriers. The common for both TIS recycling and re-use barrier is the lack of guidance of search and shared vision of government on the emerging industries around end-of-life EV batteries. The current regulations on waste in the country follow the EU Battery Directive and therefore acquires similar weaknesses. Namely, for recycling industry the obligatory recycling rate is too low. The innovation and development of the recycling processes have already reached higher rates. This means that waste regulation does not create the pressure for further innovations. It has been also noted that battery collection requirements are also low. Moreover, while the Battery Directive promotes the innovation of new efficient recycling processes, it does not encourage its practical implementation. Additionally, the legislation does not regulate recycling of specific critical materials. This means that the raw materials' low price reduce the incentives to recycle them. Therefore, considering these aspects the suggestion for policymakers would be to develop regulative framework which would strengthen the recycling requirements. At the same time, the incentives to recycle economically non-valuable materials should be provided, in order secondary materials can compete with the virgin ones.

Moreover, the Waste regulation does not specify the options of the second-life EV batteries. The lack of transparent policies for energy storage and second-life EV batteries is the major obstacle to their adoption. Therefore, policymakers could distinguish the second-life as alternative to handle waste EV batteries prior to recycling, set up the direction of search, and create protective space for niche development for second-life EV LIB market to grow. The government could develop the regulatory framework and standards for battery storage applications in cooperation with industrial players, considering more favorable conditions for end-of-life LIBs. This can be done by, for example, providing economic incentives in form of subsidies or tax credits. The regulatory framework has to provide long-term goals which companies and actors could rely on. In this way the legitimacy of the second-life batteries will be also increased.

Other policy interference might be relevant:

- For both recycling and re-use TISs the process of dismantling plays an important role in terms of costs reductions. Therefore, the knowledge and competencies development, as well as dismantling infrastructure capacity could be encouraged. Thus, the stimulation of R&D for dismantling is required.

- To encourage the growth of demonstration and pilot RD&D projects as it will pave the way for future commercial projects and provides incentives for newcomers.
- The competition between re-use and recycling should be controlled, in order to prevent the batteries with sufficient capacity to be recycled instead of re-used when it is possible.
- Improve coordination between battery pack manufactures and dismantling companies.
- Stimulate development of new business models for second-life batteries applications.
- Support the experimentation by providing subsidies or tax credits.
- Limit export of the end-of-life batteries. The development of battery re-use industry will also contribute to the batteries stay within the country, what in turn will secure constant input for recycling.

7. Conclusion

Electrification of road transport is an attempt of countries to weaken the dependence on fossil fuels and reduce CO2 emissions from the ICE cars. Yet, the electrification of the transport sector in the near future may lead not only to the decrease of CO_2 emissions in urban areas but also to undesirable environmental consequences from the extraction of raw materials required for the production of new lithium-ion batteries, and the emergence of large number of waste batteries. An absence of a certain strategy addressing these issues can nullify the efforts to overcome the climate change crisis. Norway, which leads the world race in EVs adoption, however, does not have a conclusive strategy for the subsequent disposal or second use of retired lithium-ion batteries. Consequently, the objective of this thesis was to answer the main research question: *How can a new industry emerge around the end-of-life EV batteries in Norway?* In order to provide an answer to research question two sub-questions were asked: *"What are the main drivers and barriers for the EV battery recycling and re-use?"* and "*How can public policy stimulate new industry formation in these areas?*" through the use of Technologic Innovation Systems framework. Moreover, Li-ion battery is a multi-component technology with complex value chain. In order to understand the innovation processes along the value chain and reveal how these processes influence the focal TISs, an extension to the TIS framework of the multi-technology interactions was implemented in this study.

An important for the study assumption was that Li-ion battery is a multi-component technology with complex value chain. The technology map tool was used in order to understand the battery upstream and downstream sectors, as well as reveal the interactions between these sectors and the focal recycling and re-use. This analysis followed by the implementation of conventional TIS framework. The TIS framework was used in order to understand the emergence of industries of recycling and re-use around the end-of-life lithium-ion batteries applied in electric vehicles, reveal understand the drivers and barriers of the TISs and identify bottleneck which can be addressed by policymakers.

The approach implied several stages of analysis. First, the structural analysis was used in order to map the actors, institutions and networks which participate directly or indirectly in the formation of the TISs. It showed that in the TIS recycling the actors are gathered in formal networks under the R&D projects. None of them recycle the EV batteries at the moment. The major reason for this is the small volumes of spent batteries on the market. Meanwhile, the actors develop their knowledge base, experiment, and aim to develop new recycling processes. Most of the actors engaging with research and development are large companies with prior experiences and competencies. Moreover, the R&D projects´ participants include industrial actors, research agencies and knowledge organizations. Therefore, the actors are in the process of creating strong linkages, that might help TIS to develop further. The structural components of TIS re-use are more scattered. The market actors to a large extent experiment in small groups of actors, without creating formal networks. However, the actors are more diverse, and the number of newcomers grows. The knowledge development patterns differ between TISs. While recycling TIS can be characterized by the research in the labs and testing facilities, for TIS re-use the major source of knowledge generation is RD&D projects.

The next stage of TIS analysis implied the functional analysis of each TIS with consideration of the multi-technology interactions revealed earlier. The analysis showed that not all of the TIS functions are influenced by the innovation processes along the battery value chain. The most vulnerable functions in this regard occurred be the function of knowledge development and market formation. It means that policymakers should pay attention to these functions considering wider contexts and developments in the battery value chain.

For both recycling and re-use the market driver is the transition in the transport sector from conventional cars to the electric vehicles. The favorable policies and strategies promote the expansion the EV market and the diffusion of the EVs, subsequently the Li-ion batteries.

Additionally, the development of complementary technologies, e.g. charging stations, influence diffusion of the electric vehicle fleet. In turn, the higher volumes of batteries will increase the need to recycle the end-of-life batteries, or reuse them. The energy transition and subsequent diffusion of the renewable energies, e.g. PVs, might also have effect in the increasing need for battery storage. This necessity will accelerate the new battery production, in case the second-life market does not evolve.

The very central bottleneck for both recycling and re-use TISs is the creation of legitimacy. At present, the Norwegian institutional conditions do not promote neither recycling nor re-use of EV batteries. Even considering the presence of the Waste regulations, none of the sections promote the local recycling (meaning that batteries can simply be sent for recycling to other countries), no utilization of second-life batteries. Considering the contribution that recycling and re-use of EV LIBs can make for legitimization of electric vehicles, these two industries are highly ignored.

To conclude, Norway is in a unique position to construct a well-functioning innovation system around the re-use and recycling of the EV batteries. The growing EV fleet and renewables in the country will accumulate batteries which can create an opportunity to accelerate the energy transition. The sustainable management of LIBs will accordingly increase the legitimacy for electric vehicles and strengthen its competitiveness against the conventional cars. The synergies with the electricity sector, and more precisely RES technologies, will have a favorable effect on technologies propagation. Moreover, the establishment of new industries can assist to overcome the oil and gas dependency. Therefore, the policymakers must closely consider the intervention in the TISs, with bigger priority to the second-life TIS. Current legislation is more in favor of recycling, and the large value of the batteries might be lost, including the value that might have been provided to the electricity sector.

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Appendix

Drivers and barriers TIS Re-use

Function	Drivers TIS	Potential barriers TIS	Multi-technology interaction effects
Knowledge development (F1)	- Research projects and applied cases	- The lack of new cost-effective business models in various applications; - Lack of involvement of knowledge institutions.	- Lack of knowledge on battery pack designs; - Lack of data on LIB lifecycle LIB in EV; - Lack of research on dismantling processes
Entrepreneurial Experimentation (F2)	- The financial support of the RD&D projects; - The willingness of public organizations to implement environmentally friendly technologies; - Developments in other countries.	- The lack of demonstrational projects - The high costs of the batteries;	
Market formation (F3)	- Presence of companies in partnership which provide the spent batteries on the market	- Lack of financial stimuli to commercially reuse LIBs; - Lack of standardization and regulation; - Poor availability of second-life batteries; - Unclear ownership of the LIBs	- Complementarity with RES/power grid - Competition with new batteries;
Resource mobilization (F4)	- Public funding of R&D projects	- Lack of financial incentives for retired LIBs adoption	- Might be lack of human resources for dismantling - High costs of the battery dismantling
Influence on the direction of search (F5)	- Growth in experimentations - Development of international market	- No clear vision among stakeholders - No clear vision from the government - Lack of knowledge on battery 1st life decrease technology and market expectations -	- Priority to recycling prior to second-life; - Growing EV and RES markets
Creation of Legitimacy (F6)	- Environmental benefits - Willingness of actors to improve regulations	- Lack of supporting regulations - Lack of shared vision across government and actors - Possible resistance from battery OEMs - Uncertainties in technology performance	- Complementary effect on the creation of the EV legitimacy

Drivers and barriers TIS Recycling

Function	Drivers TIS	Potential barriers TIS	Multi-technology interaction effects
Knowledge development (F1)	- R&D projects and formal networks	- Lack of knowledge on material flow	- The need for information on changing cell chemistries - The need for knowledge and competencies, and infrastructure on dismantling
Entrepreneurial Experimentation (F2)	- The participation of well-established actors and research organizations	- Access to batteries for experimentations	
Market formation (F3)		- Small volumes of retired batteries - Reliance of Government only on business actors	- Less expensive cells would reduce stimuli for recycling -
Resource mobilization (F4)	- R&D funding - Involvement of market actors	- Might be lack of human resources for battery dismantling - Not sufficient infrastructure	
Influence on the direction of search (F5)	- EU strategy to move from linear to circular economy; - Waste Regulations in Norway and EU Battery Directive; - Prior competencies and experience of incumbents; - Expectations on EVs fleet growth; - Willingness to weaken the dependency on Asia -	- Low recycling rates - No clear Government strategy	- Growing EV market - Energy transition
Creation of Legitimacy (F6)	- Willingness of actors to improve regulations - Willingness of actors to improve standardization	- No explicit government intentions to establish battery recycling industry	- Complementary effect on the creation of the EV legitimacy

Interview guide

General questions to start with:

1. Can you tell me about the project?
2. Who are the key actors within the project?
3. What are the roles of different actors taking part in the project?
4. Is your business model based on previous experience from other countries/competitors or will it be a completely a new?

F1 – Knowledge development and diffusion

1. What are the practices of exchanging knowledge between science and industry? Do you think it is enough knowledge exchange?
2. Do you follow the development of technologies?
    2.1. Is this knowledge necessary for further development of the technologies in Norway?
    2.2. Is the knowledge exchange sufficient?

F2 – Entrepreneurial experimentation

1. Do you perform some experiments, demonstrations?
2. Do you know about other firms/organisation who experiment?
3. Are there some commercialized projects?

F3 – Market formation

1. Which factors make you believe that Norway is a proper place for developing and further commercialization of recycling/re-use?
2. What are the main drivers of the market formation in Norway?
    2.1. Does the market evolve naturally or is it formed by the government?
3. In what way the development of battery reuse in the country will influence the recycling industry (if it will)?
4. Is the battery recycling industry competitive in nature? And why?
5. Will the market of Li-ion battery recycling/re-use need the government support in future?

F4 – Resource mobilization

1. What stage is the infrastructure for the recycling facility at?
2. Will the recycling facility need the skilled labor with special competencies? Do you have an access to the professional workers?
    2.1 Are the technologies for the automatization of the process in place?

2.2 What are the barriers for the automatization development?

3. Where are the financial funds coming from? Government, private sector, subsidies?
4. Where the largest part of the funds goes to? R&D, infrastructure, else?

F5 – Guidance of the Search

1. What factors or events make you believe that Norway is a suitable place for development and further commercialization of the recycling/re-use of Li-ion batteries?
2. What are your expectations regarding the technologies and prospects of the industry?
3. What are the uncertainties regarding the technologies and prospects of the battery recycling/re-use industry?
4. What are the effects of current battery or recycling/re-use related regulations on the technological development and industry in Norway?
5. In what way the regulations can be improved in order to accelerate the technological development and to reduce uncertainties?

F6 – Legitimacy creation

1. Do you meet any resistance? From citizens, producers/ importers of the diesel cars, media, government, etc.?
2. Were there any barriers in the process of receiving the financial support, approval of the project?

Interviews

Company/ Organization	Description	Position in the company	Code	Date of the interview	Duration/ min
Norsk Hydro ASA	Aluminum and renewable energy company	Chief Engineer	1	05.06.2019	60
Glencore Nikkelverk AS	The company produces high quality nickel, cobalt, sulfuric acid, copper and precious metals	Senior Specialist	2	05.06.2019	60
Norsirk AS	NORSIRK is an approved producer responsibility scheme for EE products, batteries and packaging.	Chief Adviser - Batteries	3	05.07.2019	100

Abmas Electro AS	An electrician company.	CEO	4	26.06.2019	60
Lyse AS	An industrial group within energy, infrastructure and telecommunications.	Senior Business Developer	5	09.08.2019	60
Culture and Sports Construction Oslo KF/ (Kultur- og Idrettsbygg Oslo KF (KID))	A municipal enterprise in the municipality of Oslo, which is responsible for designing, building, managing and operating cultural buildings and sports facilities in Oslo.	Section Manager and Energy and Environment Adviser	6	14.06.2019	60
NCE Eyde Cluster	Norwegian Center of Expertise Sustainably Energy Industry	Research Manager	7	09.07.2019	60
Farco AS	The firm imports products in independent, mobile heat and electric energy.	CEO	8	10.07.2019	120
Eaton AS	A power management company	Project Manager	9	16.07.2019	60
Norwegian Environment Agency (Miljødepartementet)	A government agency under the Ministry of Climate and Environment	Senior Adviser	10	21.08.2019	45