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Driving forces and obstacles to nuclear cogeneration in Europe: Lessons learnt from Finland

Highlights:

- Nuclear cogeneration could support a sustainable EU energy transition.
- A comprehensive case study of the Loviisa 3 nuclear district heating megaproject.
- Obstacles arise within market, institutional and financial frameworks.
- Distinctive stakeholders have opposed perceptions of benefits, costs and obstacles.
- Greater recognition of nuclear waste heat is needed in the future EU energy policy.

Abstract

Nuclear power plants generate electricity and a large amount of waste heat which is valuable for cogeneration. District heating (DH) is a suitable technology to decarbonize the European heat sector. By contrast with most of nuclear non-electric applications, nuclear district heating (NDH) has already been implemented in Europe, thus providing us with some valuable empirical insights. This paper investigates the forces and obstacles to nuclear cogeneration by looking at the Loviisa 3 NDH project in Finland. The key forces are energy efficiency, decarbonization of the heat sector, operational competitiveness of future nuclear technologies, and synergies with renewable energies. The key obstacles are split incentives, electricity prices volatility, inexpediency of business models and regulatory frameworks, electioneering of local authorities and pessimist expectations with regards to project financing. Policy makers should recognize nuclear plants alongside other utilities generating large amounts of wasted heat. International cooperation programs involving both nuclear and heat stakeholders should be encouraged. EU28 Member States wanting to promote nuclear cogeneration may consider providing support for the electricity generated by high-efficiency plants.

Keywords:

Nuclear, cogeneration, district heating, energy megaproject, sustainability, Finland.

1. Introduction

The most common type of nuclear power plant (NPP) in operation (277 out of 438) or under construction (59 out of 70) (IAEA, 2015) is the Pressurized Water Reactor (PWR). The thermodynamic efficiency of a PWR is around 33%. Therefore, about two thirds of the heat generated by the nuclear fuel is wasted. Since the steam exiting the high-pressure turbine is superheated, it could be used for non-electric applications such as district heating, desalination of sea water, industrial process heating etc. (IAEA, 2003). Nuclear cogeneration plants (NCP) are defined as NPPs targeting a high thermal efficiency by generating both electricity and heat. It thus excludes hydrogen production from alkaline electrolysis. A PWR can be converted into an NCP without jeopardizing the reactor’s safety (STUK, 2009: p. 6).

The thermal efficiency of NCP could reach up to 66% (ISNP, 2014), increasing the total energy output by at least 50% (IAEA (International Atomic Energy Agency), 2016a; Locatelli et al., 2015) compared to a NPP of similar features generating only electricity. Operating a PWR as a NCP implies to reduce the electricity output of the reactor. Lost electricity production depends on the temperature and the amount of heat considered. Several studies pointed out that, for the temperature ranges useful to district heating networks (85-115 °C), NCP can be designed so that the amount of thermal energy (MW(th)) recovered is five to six times greater than the electricity losses (MW(e)) (IAEA, 2017; 2016a; 2003).

Among the nuclear non-electric applications, district heating (DH) and desalination benefit from the largest industrial experience worldwide (IAEA, 2017, 2003). In Europe (including Russia and Ukraine), nuclear district heating (NDH) is the most tried-and-tested technology, and it certainly has the highest potential in the short run. Lately, technico-economic studies have been led to explore regional opportunities for the deployment of large-scale NDH projects. In Finland, Fortum (the second largest Nordic power company) offered to operate the planned Loviisa 3 NPP in a partial cogeneration mode (Fortum Power and Heat Oy, 2009: p. 26-28). In France, the possibility of transporting between 1500 MW(th) to 3000 MW(th) heat from the Nogent-Sur-Seine NPP to Paris over 110 km has been examined (Jasserand and Devezeaux, 2016; Safa, 2012). Similarly in Poland, an economic analysis was carried out for the Choczewo and Zarnowiec NPP (Jaskólski et al., 2014). The thermal output was about 250 MW(th) and the length of the main transport line varied between 22 km and 64 km depending on the town considered (Wejherowo, Reda, Rumia and Gdynia).

The implementation of such immense projects would imply an initial investment up to 1-2 billion euros alongside new agreements between utilities (Bergroth, 2010; Jasserand and Lavergne, 2016; Safa, 2012). For these reasons, they can be referred to as "megaprojects" in the sense of Sovacool and Cooper (2013). Similarly to other energy megaprojects, NDH would certainly attract a high level of public attention and political interest because of the substantial direct and indirect impacts on the community, environment, and budgets (Van de Graaf and Sovacool, 2014). If NCP is ever integrated into the EU's sustainable energy transition, there will be a number of obstacles to overcome as e.g. inexpediency of business models and regulatory frameworks or electioneering of local authorities. Prospective explorations are important to reduce the likelihood of future projects being overwhelmed by hidden costs and to limit delay in implementation. Given these considerations, this article sets out to answer and discuss the following questions:

i. What are the driving forces for the deployment of nuclear cogeneration in the EU28?
ii. What are the obstacles to the deployment of nuclear cogeneration in the EU28?
iii. What can be done to enhance the recognition of nuclear cogeneration and to prevent the failure of future similar megaprojects?

To that purpose, we led a case study based on the Loviisa 3 NDH project in Finland. Our analysis suggests that NDH megaprojects will always involve trade-offs and invariably will create winners and losers.

The paper is organized as follows: Section 2 is an extensive background Section that introduces NDH to the literature on energy policy. It includes a discussion on the driving forces to nuclear cogeneration in the EU28 (2.1), an overview of NDH experiences (2.2), a description of the singular Loviisa 3 NDH project (2.3) as well as the conceptual framework which supported our analysis (2.4). Section 3 describes the methods followed to conduct the case study. Section 4 details the experience and lessons learnt from the Loviisa 3 NDH megaproject. Actions designed to improve the recognition of nuclear cogeneration are also discussed. Finally, our conclusions are drawn in the fourth and last section.

2. Background

2.1. Driving forces to the deployment of nuclear cogeneration with PWR

In the past, long-distance, large-scale NDH have been disregarded because of high losses and inefficiency, considering that the NPP is generally located far away from urban crowed areas. Nonetheless, the extension of DH over the last decades has led to improvements in low-temperature heat distribution, and there is potential to further reduce heat losses (Li and Wang, 2014). This opens new opportunities for energy projects involving the transport of heat over long distances (Ma et al., 2009), such as nuclear cogeneration.

Cogeneration goals are in line with the EU plans for a low-carbon society (EC, 2012a), particularly energy efficiency (EC, 2009; 2012b). The European heat sector accounts for about one third of the carbon emissions in the EU28 (EC, 2016). Although the heating sector is moving towards low-carbon energy, 75% of the heat still comes from fossil fuels (nearly half from gas; IEA, 2015). According to the recent Heat Roadmap Europe, DH is one of the main technologies to deploy if we intend to decarbonize the heat sector and should be increased from today's level of about 10% to 50% in 2050 (STRATEGO, 2015a). Application of the Directive 2012/27/EU require the industries and power plants producing large quantities of excess heat to consider connection with DH networks through cost-benefit analysis (EC, 2012b: article 14). However, most EU member states chose to exempt their nuclear plants from analyses. And yet, similarly to excess heat recovered from industrial processes, the carbon emissions avoided by the use of NCP are equivalent to the carbon dioxide emitted by the heat sources that the nuclear heat would effectively replace. Besides, the use of nuclear heat would reduce the energy dependence from imported fossil-fuels.

The directives and programs mentioned above are general and nuclear energy is not specifically mentioned. Nuclear technologies are, however, identified in the EUROPAIRS (2009) project under the European Union's 7th Framework Program (FP7) for European cogeneration markets (Angulo et al., 2012). The sustainable nuclear energy technology platform (SNETP) in collaboration with the EC conducted the ARCHER (2015) project and the Nuclear Cogeneration Industrial Initiative (NC2I, 2015a), which fall in line with the European Union's strategic energy technology plan (EC (European Commission), 2015a). More recently, the Nuclear Energy Agency's working group focusing on the role and economics of nuclear cogeneration in a low-carbon energy future has been targeting the development of a generic method to assess the economic and environmental potential of nuclear cogeneration (NEA, 2015). The shared goal of these programs is to prepare the future nuclear cogeneration technologies and markets. On one hand, future reactors will generate higher-temperature heat, thus widening the range of market applications (Locatelli, 2013; NC2I, 2015b; Ruth et al., 2014). On the other hand, small modular reactors (SMR) are increasingly regarded by policy makers and stakeholders as a viable option to decarbonize both electricity and heat sectors (Carlsson et al., 2012). As for example, the Energy Technology Institute of the United Kingdom recommends to investigate further the potential of small and modular reactors to provide low carbon district heating (Middleton, 2015). A review of potential SMR technologies for cogeneration is presented in Locatelli et al. (2017), while a focus on desalination (one of the most attractive option) is presented in Locatelli et al. (2015). Compared to large nuclear reactors, SMR may be advantageous to address cogeneration markets; and this because:

- SMR may be easier to deploy close to urban areas thanks to high safety standards, thus limiting the major cost of building a heat transport pipeline (Kessides, 2012; Locatelli et al., 2014; Sainati et al., 2015).
- SMR may be faster to deploy (shorter time period from planning to operational phases). This could facilitate the development of suitable business models for those industrial clusters which aim to build and amortize a NCP and industrial plant factories during the same period of time (Green et al., 2009). If SMR are largely deployed in the future, they could benefit from positive learning by doing effects (Boarin et al., 2012). Hence, in the mid-term, policy makers and stakeholders may expect SMR to be built in a shorter time period than larger reactors.

Overall, it seems reasonable to say that the optimal size of NCP should be determined on a case by case basis. Questions which may help making a choice are e.g. 'What is the size of the heat demand?'; 'Is the building of SMR instead of larger reactors likely to allow the sitting of nuclear units closer to consumption sites?; 'Can we expect a shorter deployment time if building several SMR?''

Another driver identified resides in the potential synergies which could be generated by the joint use of NCP and renewable energies. Heat from nuclear plants could enhance biofuel feedstock production, thus making savings in valuable byproducts (such as lignin), which are currently consumed in the biorefinery boilers (Greene et al., 2009; IAEA, 2009; NETNUC, 2011). Instead, these byproducts could be used for other industrial applications (e.g. automotive parts, wood panel products; Laurichesse and Avérous, 2014). As concerning the French case, Cany et al. (2016) argue that the nuclear fleet could take advantage of intermittent renewable sources to produce valuable byproducts and thus accomplish two feats with one action: provide flexible services for the power system and produce byproducts such as heat or hydrogen.

The various levers described above tend to show that NCP can be a valuable asset for the sustainable EU28 energy transition. It is therefore important to better understand those mechanisms which can result in overwhelming costs and delay in implementation. For this reason, studying the obstacles that NCP projects must overcome is essential if we intend to draw lessons for stakeholders and policymakers. NDH is the most experienced nuclear non-electric application in Europe and is thus ideal for empirical investigations.

2.2.NDH experiences

Experience in NDH includes 52 NCP in 8 countries for over 30 years (see Table 1). These cases all imply the cogeneration of heat and electricity, but experimental reactors dedicated to heat production only have also been considered (e.g. the 1976 “Thermos” project by the French Nuclear Energy Commission (CEA) which planned to build 50-100 MW(th) reactors; IAEA, 1997). The heating capacity provided by these NCP fall in the range of 5–250 MW(th), generally a minor fraction of the total reactor thermal power. In these systems the water is supplied to 130-150°C in winter by using steam from the lower pressure turbine (about 80-90 °C), which is reheated by steam extracted from the back of the high pressure turbine. It is lowered in summer to 85°C by using only the low-temperature heat exchanger. Such high temperature were needed to compensate the high thermal losses of past heat transportation systems. Thanks to the improvement of insulation technologies, supply temperatures of DH networks tend to decrease and efficient networks range between 85-115 °C (in a typical Finnish DH system, different countries have different settings, e.g. in Denmark the use of lower supply temperatures is common). It is thus expected that future NDH system will only require extracting steam from the lower pressure turbine, with fewer reduction of the electricity output. The heated water is then pumped in a closed pipeline to the distribution stations where the heat is transferred into the intended local DH network via heat exchangers. The distance between the NCP and the DH system is relatively short in all cases: an average of 10 km, with two exceptions in Russia (Kola, 64 km and Novovoronezh, 50 km). Return water temperatures to the NCP are approximately 50-70 °C. To meet high-reliability requirements, NDH systems require a backup heat source to be used when the nuclear heat supply is disrupted. These projects were relatively small financially speaking and almost never necessitated cooperation between an NCP operator and DH network operator (the exception being Ågesta in Sweden; NC2I, 2015c). All these cases are of pretty low level of complexity and cannot be referred as megaprojects (in the sense of Sovacool and Cooper, 2013). Thus, they cannot be used to answer our research questions which concern NDH megaprojects with fragmented stakeholders.

Here Table 1

2.3. Case description

In line with our research questions, we selected the only NDH megaproject that reached feasibility: the Loviisa 3 NDH megaproject from Finland. It was proposed by Fortum as a part of an application for a decision-in-principle concerning the construction of the Loviisa 3 reactor (Fortum, 2009: p.26-28). The aim of the project was to develop a new PWR (or boiling water reactor, both options were investigated) to be operated in cogeneration (800-1300 MW(e) and 1000 MW(th); Bergroth, 2010; ISNP, 2014), alongside with a 1000 MW(th) heat transportation system (Paananen and Henttonen, 2009). It was to be built on the existing site of the Loviisa twin-reactor NPP site, approximately 80 km east of the Helsinki metropolitan area (i.e. Helsinki, Espoo and Vantaa; see Figure 1) with one million inhabitants. The DH consumption in the area typically varies from a minimum of 400 MW(th) in summer to a peak of 3500 MW(th) in winter. Around 90% of the heat is currently supplied by coal and natural gas-fired plants (Helen, 2015a), accounting for 50% of greenhouse gas emissions in Helsinki (City of Helsinki, 2015).

Unlike the previous operating systems described in Section 2.2, the Loviisa 3 NDH megaproject addressed three new main technical challenges:

i. Cogeneration with a Generation III PWR or BWR;

ii. Extraction of the largest amount of DH from a reactor;

iii. Construction and operation of the longest pipeline required to transport the nuclear heat to the city.

Here Figure 1

The amount of heat it planned to provide represented about 60% of the DH consumption in the Helsinki metropolitan area: 7 TWh out of 12 TWh per year (see e.g. ISNP, 2014). By contrast, the consumption of the DH network owned by Fortum accounts for only 2.5 TWh. Thus, close collaboration between Fortum and other DH operators (Helen and Vantaan Energia) would have been necessary. Because Helen and Vantaan Energia are municipality-owned (respectively by municipalities of Helsinki and Vantaa), the project would have required agreement or support from municipalities. The municipality-owned energy companies are subject to guidelines and regulations drawn up by municipal decision-making bodies such as the municipal council. The municipal council decides the objectives of energy companies and appoint their board of representatives. Companies need to have the formal endorsement of the municipal council before deciding on e.g. large investments, tariff changes or major policy issues. The municipality-owned energy companies also have to adhere to ordinary legislation governing private limited companies. Figure 2 depicts the current configuration of stakeholders surrounding the Loviisa NPP and the DH networks of the Helsinki metropolitan area.

At present, the Loviisa 3 NDH megaproject is but an idea on paper and the obstacles hindering its implementation remain. Yet the inherent complexity makes it a very interesting case to study, providing lessons for future NDH megaprojects.

Here Figure 2

2.4. Conceptual framework

The problem with this case is that, despite being feasible, it did not go ahead. Regardless of the cogeneration option, Fortum has never been granted the license to start building the Loviisa 3 NPP. The Finnish law states that utilization of nuclear energy must be “safe and not to cause harm or damage for the people, environment or property” and be “in aligned with the overall benefit of the society” (Ydinvoimalaki – Finnish law on nuclear energy, 1987: articles 5 and 6). Fortum's application for a decision-in-principle on the construction of the new Loviisa 3 unit was rejected by the government in April 2010. In July 2010, the Finnish government approved the construction of the Olkiluoto 4 reactor (owned by an established company - TVO) and the Hanhikivi 1 reactor (owned by a new supplier – Fennovoima Oy; see e.g. World Nuclear Association, 2017). This was decided in line with the EU objective of opening electricity markets to competition (EC, 2009: article 8; 2012: article 1). Yet the decision-making process may have also been affected by other factors such as e.g. public discussions or considerations related to political party dynamics.

Nonetheless, the fact that our case “failed” does not make it less deserving of inquiry. Discussions on the technical development of technologies mostly investigate successes, leading to a biased narrative about “winners” that blind energy analysts to the multifarious ways that energy projects can fail (Sovacool, 2014). In the words of the historian Braun (1992: p.214), “*In analyzing technological development, failed innovations are just as important as, and possibly even more so than, successful ones*.” Because failure is more frequent and probable than success, we can learn even more by studying it (Smil, 2010).

For the literature on megaprojects, there exists a threshold above which projects generate so much interest, so much value, and so many variables that conflict overcomes rational discernment and the real costs exceed benefits (real costs in money, in social upheaval, in environmental damages; Flyvbjerg, 2016). The failure of megaprojects may result from biased and inflated projections made by project sponsors (Flyvbjerg, 2009). Given their size and complexity, megaprojects typically have many stakeholders involved, each pushing their own agendas (Miller and Hobbes, 2009). Authors agree on the fact that stakeholders are often ill-prepared to face the inevitable turbulence that such a project inevitably creates (Sanderson, 2012). To anticipate future difficulties, a broad assessment of how it affects corporations, communities, governments and ecosystems should be conducted (Van de Graaf and Sovacool, 2014).

The authors that study NPP projects have found sources of failure similar to others megaprojects as e.g.: overoptimistic estimations, first-of-a-kind related issues and undervaluation of regulatory requirements (Locatelli and Mancini, 2012). Analyzing the unforeseen problems that occurred during the construction of the Olkiluoto 3 NPP, Hellström et al. (2013) highlight the importance of building relationships and securing commitments between key players during the early stages of a project. In the same vein, Ruuska et al. (2011) developed a new theory of governance in large projects by adopting a project network view with multiple networked firms within a single project. It encourages a shift from the prevailing narrow view of a hierarchical project management system towards an open system view.

Despite providing useful analytical tools, these theories do not explore NCP projects. The literature on nuclear cogeneration has always addressed technical or economic aspects (Bergroth, 2010; Reński et al., 2014; Jasserand and Devezeaux de Lavergne, 2016; Safa, 2012; Paananen and Henttonen, 2009). Thus, debates on nuclear cogeneration currently disregard the social, political, institutional and psychological dimensions (exception being the conference paper mentioned in Section 3.1, which implied interviews with NDH utilities in Hungary, France, Switzerland, Norway and Japan: NC2I, 2015c). To fill this research gap, comprehensive case studies of NDH experiences are necessary. It would help to anticipate and prevent future difficulties that are inevitable when dealing with real projects. Because of its unique features, the Loviisa 3 case justifies a specific analysis.

This article employs a conceptual framework derived from the “barriers theories” to explore the sources responsible for the failure of the Loviisa 3 NDH megaproject. These theories study the mechanisms that inhibit the deployment of technologies which are both energy-efficient and (potentially) economically efficient (Sorrell et al., 2000). An interesting contribution to the discussion is offered by Weber (1997), who has classified obstacles as institutional, economical, organizational, and behavioral. However, the taxonomy adopted in this article is an adaptation of that proposed by Chai and Yeo (2012) which groups obstacles into the following categories:

- *Market failures:* As neoclassical economists posit, the allocation of goods and services is not always efficient. Energy projects can fail because of information asymmetries, split incentives, principal-agent problems, or externalities.
- *Physical constraints:* As technological systems theorists argue, energy projects can fail technologically. The larger and more complex energy projects become, the more susceptible they become to technical problems, delay, and costs overruns.
- *Institutional:* As energy politics theorists suggest, energy projects can fail because of their inability to break through deeply rooted regimes boundaries, unsuitable business models, regulations or enforcement and priorities, experience and electioneering of local authorities.
- *Financial:* As financial theorists predict, energy projects can fail because of features that are ill-suited to the current liberalized EU28 energy market. Energy projects often present long-term payback periods and are often considered by private investors as risky assets.
- *Behavioral:* As sociologists posit, energy projects can fail because of resistance to change from individuals, a lack of common objectives and values, or a low level of trust between stakeholders.

These five assumptions were deducted from the existing literature by Chai and Yeo (2012), and their plausibility was probed with regards to the Loviisa 3 NDH megaproject. The fifth category has been disregarded as behavioral aspects are implicitly present in all the other categories. Colmenar-Santos et al. (2015) also adopt this framework to discuss the obstacles blocking the deployment of fossil-fuel cogeneration plants. Furthermore, these assumptions overlap those made by Sovacool and Cooper (2013) to discuss the governance of energy megaprojects, namely social, economic, technical, political and psychological.

3. Methods

By applying the ‘barriers theories’ framework to the Loviisa 3 NDH megaproject, we conducted a disciplined interpretative case study, according to Odell (2001). Such research is particularly suited for cases that are “recent or seem intrinsically important” (Odell, 2001); it allows us to sharpen and refine existing theories while working with them. Easterby-Smith et al. (2015) helped design the case study, which aims at answering the research questions mentioned in the introduction. The sampling gathers views from a medium sample of people likely to have different perspectives and experiences (see Appendix A for the details of in-depth interviews). Individuals were selected with regards to their knowledge of Finnish energy systems and of the Loviisa 3 NDH megaproject in particular.

The data for the case study has been collected through semi-structured interviews as well as by examining the relevant documents. Following the principles suggested by Yin (2014), the topic guide has been designed to favor the emergence of plausible alternative explanations, avoiding predictable answers. The first set of questions were general questions such as e.g. “what are the factors driving the political process in Finland? In Helsinki? What are the most relevant technologies for the future heat sector of Helsinki? Why?”. With respect to question (ii): *“What are the sources of failure of NDH megaprojects?”,* insights from VTT (the largest technical research center in Finland), the Finnish Ministry of Employment and the Economy (TEM), the Finnish Radiation and Nuclear Safety Authority (STUK), the City of Helsinki Environment Center and the Environmental Committee of Helsinki, have been particularly relevant to our study. Moreover, triangulation was used, i.e. the same questions were put to all the respondents. This made it possible to obtain a broad assessment of how the project would affect stakeholders. Insights from the operators Fortum and Helen were particularly useful, as they would have been the most impacted by the implementation of NDH. With respect to (iii): *“What could be done to enhance the recognition of nuclear cogeneration and to* *prevent the failure of future NDH projects?",* insight from the Ministry of Employment and the Economy has been highlighting. Also, some interviewees took part in the NC2I (2015a) international program on nuclear cogeneration, providing valuable materials.

All the interviews have been recorded (except for one due to confidentiality issues) and then transcribed. Using the principles offered by Silverman (2013), attempts were made to limit personal bias by:

i. Looking for examples that might disconfirm current beliefs
ii. Constant comparison through triangulation
iii. Comprehensive data treatment and tabulations, implying greater rigor in organizing data and accepting the fact that quantitative methods can be relevant to complete a qualitative approach.

Cross-pollinating insight from the in-depth interviews with perspectives from the literature made it possible to build a questionnaire. It was based on views from 17 VTT individuals and 10 Fortum individuals. VTT individuals were chosen because of their expertise on energy systems, and in particular DH. Fortum individuals were chosen because of their implication in the feasibility study for the Loviisa 3 NDH megaproject. Quantification from the ranked questionnaire is as follow: "Always important=1; Often important=0.66; Sometimes important=0.33; Never/Seldom important=0". As stated by Thollander et al. (2010), we must keep in mind that the analysis based on these quantifications relies on broad simplifications as the quantified results contain several more perspectives on the issue than merely a single ranking score. Furthermore, the respondents are not representative of the sampling addressed through the in-depths interviews. Nonetheless, it helped us to step back from vivid discussions which often involved strong social ideology.

4. Loviisa 3 NDH project: discussions and implications

This section answer questions (ii) and (iii) by analyzing and discussing the Loviisa 3 NDH megaproject. The complete details over obstacles to the Loviisa 3 NDH project as perceived by Fortum as well as VTT respondents are shown in Figures 3 and 4. Please refer to Section 2.3 for further information on technical aspects and stakeholders features.

Here Figure 3

Here Figure 4

4.1 Market failures and physical constraints

4.1.1. Market failures

Split incentives between the two main companies concerned by the Loviisa 3 NDH megaproject, Helen and Fortum, are perceived as a main source of failure by the interviewees. While this project is aligned with the Fortum long-term strategy to replace the old Loviisa nuclear power plants that are to be closed by 2027-2030 (TEM, 2011: p. 7), the impact on the heat and electricity markets would disturb the activities of Helen. Introducing such a large amount of heat (see Section 3.2. for details) in the market would inevitably imply the closure of a few fossil-fuels cogeneration plants since 90% of Helsinki's DH is provided by fossil-fuel cogeneration plants (Helen, 2015a). Without any suitable arrangement, Helen would have inevitably lost a significant market share in electricity to the benefit of Fortum. Helen is fully owned by the municipality of Helsinki, and therefore the municipality have a significant influence in the decision-making process of the company (see Section 2.3). The Helsinki municipality that owns Helen also owns 40% of the Vantaan Energia (the rest belonging to the Vantaa municipality), which operates the DH network of Vantaa. Thus, split incentives concern all the Helsinki metropolitan area, introducing further complexity. The Loviisa 3 NDH megaproject emphasizes the competition existing between NDH and the heat sources which are already in place. When replacing fossil-fuel cogeneration, the issue is even more complex as it implies reallocating the electricity output between energy players. This is in line with results from Broberg Viklund and Karlsson (2015) who state that the recovery of industrial excess heat in DH systems based on fossil-fuels cogeneration plants reduces the possibility of producing electricity from those plants. In the Loviisa 3 NDH case, the electricity generated from the NCP would have compensated for the reduction due to the closure of fossil-fuel cogeneration plants. Connecting the NCP to the DH system would have also reduced the need for fuel in the thermal production system. These fuel resources could have then been used by alternative users. On the system side, it is important to consider the integration of a NCP into the DH system. Obstacles arise when considering interactions between established stakeholders and the resulting trade-offs.

The solution, if there is a problem to resolve, would be to limit market trade-offs by adapting suitable contractual rules. Finnish energy companies follow a unique ownership model, the so-called Mankala principle (Puikkonen, 2010). Mankala companies are jointly owned by a number of parties that bear the investment and operating costs of the resulting company, and secure an electricity supply which corresponds to their share of ownership. Applying the Mankala principle to the Loviisa 3 NDH megaproject may make it possible to reach an arrangement between Helen and Fortum. As the electricity and heat output of the nuclear plant is shared, it would help compensating the market losses feared by Helen (and similarly by Vantaan Energia). Figure 5 depicts the ownership model that could prevent having split incentives between utilities. The pre-requisite of such a common agreement is stakeholder commitment at an early stage of the project (the lack of early commitment largely penalizes the management of the Olkiluoto 3 project; Hellström et al., 2013). With regards to the Loviisa 3 NDH option, these negotiations (if they occurred) did not lead to a conclusion. The decision-making process of such an agreement would inevitably imply further complexity. The Finnish parliament and government both play an important role in the licensing process of new NPPs in Finland. The decision-in-principle (the first step of the licensing process; TEM, 2011) needs to be approved by both the government and the parliament following a democratic process. Our empirical investigation has showed that political parties, and hence the public's opinion, must be convinced of the project's legitimacy. Once the decision-in-principle is granted, the technical requirements are elaborated with safety standards, which must be checked by the Finnish radiation and nuclear safety authority (STUK), and ultimately validated by the government. In such an immense project, foreign investors and multinationals may also be involved. Finally, the European Union (through the EC) would certainly need to support the project, or at least agree on its benefits.

Here Figure 5

Interviewees pointed out that this lack of discussions is linked to the difficulty of precisely determining the contractual rules to apply. The value of market trade-offs strongly depends on the electricity prices, which are hard to predict on long term. It makes the respective benefits and losses of Helen, Vantaan Energia and Fortum impossible to assess with certainty. To overcome the volatility of electricity prices, one solution could be to publically guarantee support for the electricity produced from NDH plants. Such a mechanism could be inspired by e.g. feed-in-tariffs (UNDP, 2012) or by the recent United Kingdom electricity market reform (Contracts for difference; DECC, 2014). Guaranteeing support for the electricity generated from high-efficiency nuclear plants is another alternative to be explored. In this case, further quantitative studies would be needed to determine the efficiency rate upon which a facility could apply for public support. Another threshold to target could be the amount of carbon emissions saved by the project.

Adaptations of the Mankala principle can also lead to innovative business models for NDH megaprojects in different contexts. In the EU28 Member States where nuclear power plants are traditionally owned by a single company, it could be applied to the production of heat only, while leaving the electricity output to the initial plant owner. In that case, the costs and benefits of heat transport and delivery would be shared, but only one company would own the nuclear reactor. It would require rigorously establishing which costs account for electricity production and which costs account for heat production. It would also require long-term contracts in which the nuclear reactor owner agrees to provide a certain amount of heat, with a fixed annual and daily production. Such discussions would certainly be highly political and an arrangement very complex to establish. Any of the EU28 Member States wanting to encourage high-efficiency nuclear power plant could initiate and moderate the discussion process between stakeholders, eventually providing standardized, long-term contracts.

4.1.2. Physical constraints

Table 2 shows the main arguments related to the Loviisa 3 NDH option as presented by Fortum and Helen respectively, as a support for the interviews. All the listed issues are relevant and true in principle. However the fact that Fortum and Helen emphasized different points shed light on their distinguished opinions and perceptions of NDH system, in accordance with the goals and strategies of utilities. Stakeholders pushing their own agendas is a common source of failure for megaprojects (Miller and Hobbes, 2009).

Here Table 2

To illustrate the high degree of subjectivity in technical debates, let us consider one technical issue: the heat back-up capacity. For Helen, the heat backup capacity is a major constraint. They emphasize not only the technical risk (on the nuclear plant and on the transmission line), but also the political risk (closure of nuclear plants after a nuclear accident in another country, such as

Fukushima Daiichi). For DH scientists from VTT, the answer is more nuanced. They highlight that there is always a significant capacity in boilers (at least in Helsinki). For Fortum and Fennovoima, the backup is not a major obstacle. They assume that the cost of building gas back-up is not prohibitive. Looking back to empirical experiences (NC2I, 2015c), most operational NDH systems require fossil-fueled back-up for operational and maintenance outages (planned in low-duty periods), and none of them encounter unexpected technical or financial difficulties related to the heat back-up system.

Quantifications from the questionnaire confirm that perceptions of the obstacles to the Loviisa 3 NDH alternative depend on the stakeholder interviewed. This is true for physical constraints (see Figure 6) and can also be observed with other kinds of obstacles (e.g. obstacles related to the role of the public authorities; see Figures 3 and 4). Regardless of the relevance and relative importance of each obstacle, which must be analyzed with caution, Figure 6 shows that individuals from Fortum perceive the physical constraints to be less important compared with research scientists from VTT.

Here Figure 6

Our analysis concludes that clashes over the technical feasibility of NDH megaprojects are not merely technical debates, but highly political contests that revolve around social ideology, values and power (confirming results from Van de Graaf and Sovacool, 2014). We clearly need a trustworthy feasibility study upon which all stakeholders can rely. For this reason, a joint cost-benefit analysis should be carried out, involving individuals from all the relevant organizations. Dynamic, multi-disciplinary working teams and trustworthy management processes focusing on the creation of shared visions are particularly important when addressing profound innovation (Raven and Verbong, 2009). Allocating the management of the study to a public research organization such as VTT should be considered. Academic institutions would also bring valuable skills to the discussion, particularly when comparing NDH to alternative solutions for decarbonizing the Helsinki DH system.

4.2. Institutional and financial obstacles

4.2.1. Institutional

Boundary-crossing innovation

Cooperation between a nuclear plant operator and a DH network operator to provide large quantities of heat to the network has not been experienced worldwide. As a matter of fact, NDH experiences are generally limited to small-scale cases where the nuclear plant operator also owns the DH network (NC2I, 2015c). Nuclear heat is obviously not among the low-carbon technologies usually considered by DH network operators (SETIS, 2012). Despite being hardly measurable, behavioral or psychological means such as "resistance to change" may have inhibited the will of investigating NDH for Helsinki.

Similar observations have been made by Colmenar-Santos et al. (2015), with regard to fossil-fuel cogeneration, which fall in line with a recent IEA (2014) report entitled "Integrating heat and electricity sectors". It is important that nuclear and heat sectors also build connections. Even though several European programs aim at discussing nuclear cogeneration openly (ARCHER, 2015; EUROPAIRS, 2009; NC2i, 2015; NEA, 2015), these groups are largely composed of nuclear stakeholders. Future workshop, seminars, energy clusters or other open networks dealing with nuclear cogeneration should integrate stakeholders from other sectors, such as DH network operators. This would make it possible to highlight and challenge established norms, routines and tacit knowledge, which are often deeply rooted (Raven, 2007). Opening these clusters can be more efficient than pure policy instruments, if the technology proves to be advantageous for society in general (Palm and Thollander, 2010).

Business model effect

Nuclear is not among the priorities of Helen, which nowadays only owns a small fraction of nuclear MWs through its ownership in Teollisuuden Voima, and produces 10% of its electricity production with nuclear (before Olkiluoto 3 start-up). In addition, such a large investment committing the DH supply of the area for decades is contradictory to the strategy of Helen (remaining open to new opportunities which may appear in the future).

Experiences in other sectors with natural monopolistic characteristics has shown that utilities will not embark on innovative activities without an incentive to do so (Greenwood et al., 2011; Bauknecht et al., 2007), and this incentive should undoubtedly come from the regulator (Hawkey and Webb, 2012). If the EU-28 Member States do not create a regulatory framework aimed at promoting NDH, then in spite of the implementation being technically and (potentially) economically feasible, the scheme cannot progress seeing that investment in NDH is less attractive than other projects that do not conflict with the utilities' distinctive business models and do not challenge established regime boundaries.

Open DH, or third party access, is an initiative that could allow nuclear operators to offer heat to the network, if priced competitively. Third-party access would mean the introduction of a daily heat production market. Any heat supplier providing competitive heat would be able to sell it to the network. By contrast, In Finland, the DH network operator determines, on a voluntary basis, how to set up the heat supply for the system. It then chooses, based on short- or long-term contracts, between own, available heat sources and possible external heat sources (Eduskunta (Parliament of Finland), 2009). While an open network is an option to consider, caution is needed before implementation. As a matter of fact, the practical impact of third-party access on the overall efficiency of the network is very uncertain, and could even lead to higher system costs without sizeable benefits (Bundeskartellamt (German Competition Authority), 2012). Based on empirical evidence from Sweden, Broberg et al. (2012) posit that it could generate profitable excess heat investments, while the Energimyndigheten (Swedish Energy Agency, 2015) disprove this finding.

Regulatory framework with regards to regional symbioses

Even though the government subsidised energy efficiency investments within the heat sector (TEM, 2014), it does not target specifically industrial excess heat recovery. Besides, the National climate and Energy strategy clearly prioritize the use of biomass to decarbonize the heat sector (TEM, 2013). Whereas Finland is in line with the objectives of the European Union concerning energy efficiency (Energy efficiency watch, 2013) and the use of renewable sources (Statistics Finland, 2015), the current state of the regulation does not encourage excess heat recovery through cooperation between utilities. This lack of political recognition of the decarbonization potential of industrial excess heat recovery, and of nuclear among those industries, clearly penalizes the Loviisa 3 NDH megaproject. Local authorities tend to over-prioritize renewable heat sources.

These observations are in line with the conclusions of Persson et al. (2014) and Connolly et al. (2014) for the EU28 (and also with: EC, 2014). According to these authors, 31% of the total building heat demand in the EU28 could be provided by industrial excess heat recovery. It is argued that "*the importance of heat has long been underestimated in EU decarbonization strategies and local heat synergies have often been overlooked in energy models used for such scenarios*" (Persson et al. 2014: p.1). Despite its forceful intentions, the Directive 2012/27/EU (EC, 2012b) do not mention the potential of nuclear cogeneration. In line with the article 14 of this Directive, EU member states submitted in 2015 their notifications regarding their energy efficiency potential in the heating and cooling sector at national level. This comprises heat recoverable from industries and power plants, but rarely include nuclear plants. In that vein, the pan-European Thermal Atlas, , a project co-funded by the EU's Horizon 2020 research program, has recently performed a thorough and valuable mapping of the EU residential and tertiary heat demand, alongside with the mapping of existing excess heat sources (STRATEGO, 2015b). While fossil-fueled thermal plants producing electricity only are mapped as 'cogeneration excess heat', nuclear plants are excluded from this study.

The authors agree with Persson et al. (2014) on the fact that the Directive 2009/72/EC should be updated to explicitly allow long-term contracts to those suppliers of technologies that comply with the environmental obligations of the EU Member States. We further advocate that nuclear plants should be recognized by the EC (and the projects funded by EU research programs) alongside other utilities generating large amounts of waste heat to be recovered.

Priorities, experience and electioneering of local authorities

Local authorities in the EU28 did not use to consider energy as a priority (ESD, 2005). Actions carried out in this area are also often “non-transparent” (Cahn, 2000). Electorally speaking, it would be dangerous to go into debt for energy projects that are not essentially open to discussion with the general public; they choose not to embark on such projects in most cases (Peters et al., 2013). In addition to these features, nuclear projects face political key obstacles related to economics, planning, public perception and waste management (Goodfellow et al., 2011; Greenhalgh and Azapagic, 2009). Nuclear energy often generate fears, as shown by the impact of accidents on the public opinion (Hayashi and Hughes, 2013; Kim et al., 2013; Thatcher et al., 2015; Visschers and Wallquist, 2013). Distrust towards nuclear power is particularly strong in Helsinki where the second largest party in the city council is the Greens of Finland. The other party is historically against nuclear – the Left Alliance – and holds 30 seats over 85 (City of Helsinki, 2016). This, coupled to the fact that the Helsinki municipality owns 100% of Helen (Helsinki DH network operator) and 40% of Vantaan Energia (Vantaa DH network operator), makes it difficult to establish a constructive debate on the possibility of heating the city with nuclear cogeneration. As depicted in Section 2.3, energy companies have boards of representatives appointed by the municipality. When the board members assume their seats, they no longer represent their political parties but rather the company, and thus must act in the best interests of the company; this often raises conflicts of interests and values (Magnusson and Palm, 2011).

To counterbalance this trend, academicians should provide reliable, impartial and qualitative studies on NDH experiences, bringing the discussions a step back from purely technical aspects and inviting the civil society into the debate. Transparent and systematic data sharing of NDH experiences should be encouraged through international cooperation programs. Russia, which has the largest experience with NDH (IAEA, 2003), should actively take part in these programs. Local authorities experiencing NDH should be interviewed and the opinion of citizens heated by nuclear heat should be collected through large-sample questionnaires. This would highlight whether or not NDH is supported by the communities that use it. Eventually, it would also provide material for NDH promotion and dissemination programs, with the aim of increasing recognition of this alternative.

4.2.2. Financial

NDH requires a long payback period and a large capital input, compared with other public works of relevance. As a matter of fact, the life expectancy of the capital asset associated with those projects may be up to twenty years (Jasserand and Devezeaux, 2016; NC2I, 2015c: p. 17), depending on the operational environment and the energy market conditions. This makes it unattractive to energy markets that have already been privatized and opened to competition since they prefer projects with shorter payback periods and smaller capital asset (Euroheat & Power, 2006; UNDP, 2012). This fact, coupled with the higher risk involved in the implementation of heat transportation systems compared with other more conventional technologies (Oxera, 2009) and with risks specific to innovative nuclear projects (Locatelli and Mancini, 2012), means that the expectations on the required cost of capital are greater. It emerges from our empirical research that, even though the Loviisa 3 NDH megaproject has not reached the financing stage, pessimist expectations shaped the stakeholders' negative perceptions of the project's feasibility. This brings to mind the so-called "self-fulfilling prophecies", a term coined by John Maynard Keynes (Keynes, 1936) to illustrate the impact of individual expectations on economic outputs. Expectations of difficulties during the project financing process may inhibit the will of stakeholders to be involved in preliminary stages.

It is complex to determine whether the risk is correctly estimated or not. What we know is that two thirds of the existing NDH systems have been financially successful (NC2i, 2015c). Failures are due to unexpected risk, changing boundary conditions, too small scale of projects (NC2i, 2015c: p. 18). NDH project assets could be valued positively by investors wanting to reduce the impact of geopolitical risks. Mari (2014) studied diversified portfolios of generating capacities and states that nuclear power is an important asset for minimizing the electricity prices. In the EU28, the cost of fuel accounts for 35% of the total operational costs of nuclear units (OECD, 2015). By comparison, these ratios are about 90% for combined-cycle gas turbines and 70% for coal technologies. Empirical experiences proved that the high volatility of gas prices relative to electricity significantly penalizes fossil-fuels cogeneration plants (Colmenar-Santos et al., 2015). NDH systems, once in operation, have the ability to maintain the price of heat within a given threshold range without jeopardizing the profitability of the infrastructure.

Mistrust commonly affects financial markets. Since the 2007 subprime crisis, a high-quality public guarantee has become a pre-requisite to the successful financing of large infrastructure projects (Weber and Alfen, 2010). Based on a comprehensive feedback of NDH projects that have been implemented, NC2I (2015c) states that two thirds of projects were financially successful, showing an average payback period of 20 years. However, these projects were relatively small compared to NDH megaprojects such as the Loviisa 3 one (see Sections 2.2 and 2.3). Our empirical investigation highlighted that the long term investment profile, nuclear and first-of-a-kind aspects of NDH megaproject assets could inhibit the will of investors to get involve in financing stages.
An approach to face this obstacle resides in the concept of 'cogeneration readiness' (Energy Technology Institute (ETI), 2016: p. 59-60). Nuclear plants build as 'cogeneration ready' could easily be upgraded to supply heat in the future by e.g. anticipating the additional space requirements for pipelines and heat exchangers. According to the ETI (2016), cogeneration readiness can be delivered

for a small incremental cost, representing approximately 10% of the total capital costs required for an actual cogeneration upgrade. The implementation of such a design would allow nuclear operators to start operating the plant in an electricity-only generation mode while remaining open to the cogeneration option if the market, business and institutional conditions become favorable. In this way, the stakeholders would not have to bear the risk specific to the cogeneration application at the same time as the risk inherent to traditional electricity-only reactors.

Facilitating the risk-sharing of low carbon assets may also help reduce the risk premium associated to NDH projects (Aglietta and Rigot, 2012). Securitization of low carbon assets should be done within a secured, institutional framework (Leurent, 2015). In the EU, actions undertaken by the European Central bank (ECB) and the European Investment Bank (EIB) have served the sustainable financing of long term energy projects by guarantying the liquidity of the associated assets (Direction Générale du Trésor – French financial authority, 2013). These actions should be further developed, and priority given to those energy projects which value added have been demonstrated both for the economy and climate change mitigation. In that vein, the ECB could accept low carbon energy assets as collateral from banks, as pointed out by e.g. *La Direction Générale du Trésor* (2013). Another effective measure could be the large-scale implementation of emissions trading or carbon taxation systems (Stern, 2006). We further agree with Stiglitz and al. (2009) on the fact that new regulations are required to further integrate natural elements such as carbon dioxide in the calculation of economic and social performance indicators.

4. Conclusion and Policy Implications

The Loviisa 3 NDH megaproject examined herein reminds us of the many obstacles to overcome before being able to deploy future nuclear cogeneration megaprojects which require cooperation between utilities and other stakeholders. Debates about the technical feasibility may be biased by political contests and social ideology, split incentives may occur, electricity price volatility may undermine the establishment of contractual rules, business models may not be adapted, and electioneering of local authorities may inhibit the will of investing in this alternative. Disconnection of nuclear and heat sectors makes it hard for such boundary-crossing innovation to break through established business models and routines. The lack of recognition of the heat wasted from industries, including nuclear, restrain the development of regional symbioses. Additionally, the financing of energy megaprojects has often been problematic in the EU28 liberalized energy markets. Whereas the main challenges have been addressed, a larger quantitative study would be needed to determine the relative importance of each factor.

Ultimately, our analysis suggests that NDH megaprojects will always involve trade-offs and invariably will create winners and losers. The "progress" that NDH may bring is value-laden, whether intentional or not. For engineers, NDH megaprojects are logistical puzzles whose value will be assessed on decarbonization and economic potential. For nuclear operators, NDH megaprojects are management issues whose value will be evaluated on the basis of strategic considerations. For DH networks operators, NDH megaprojects are an alternative, risky source of heat whose value will be gauged by comparison with other NDH experiences. For investors, NDH megaprojects are capital assets whose value will be assessed on the expected return on investment. To communities chosen to host NDH megaprojects, they are exercises in democratic participation whose value will be judged on transparency and the perception of being "good for society" or not. To public authorities, NDH megaprojects are a potential decarbonization pathway whose value will be appraised on energy transition scenarios. Alongside the feasibility study, a broad assessment of how future NDH megaprojects will affect corporations, communities, government and ecosystems must be conducted.

Stakeholders planning for NDH megaprojects may want to consider the creation of a new shared company, in line with the "Mankala principle" followed in Finland. Such project governance would reduce the trade-offs between stakeholders. In countries where nuclear power plants are traditionally owned by a single company, the Mankala principle could only be applied to the production of heat, while leaving the electricity output to the initial plant owner. In this case, costs and benefits of heat transport and delivery would be shared, but only one company would own the nuclear reactor. It would certainly require rigorously establishing which costs account for electricity production and which costs account for heat production. It would also require long-term contracts in which the owner of the nuclear reactor agrees to provide a certain amount, with a regularity to be fixed. In all cases, strong business relationships and commitment must be built from an early stage. It should start with a co-directed feasibility study, leading to results that can be trusted by everyone. Stakeholders may also plan to build future reactors as ‘cogeneration ready’, even if they are initially required to supply electricity only. ‘Cogeneration readiness’ can be delivered for a small incremental cost and would ensure that nuclear plants are ready for a subsequent upgrade to allow DH supply. This would disconnect the decision-making process and investments related to the cogeneration application from those related to the electricity-only generation; hence facilitating project management issues and financing stages.

International cooperation is primordial if we wish to share NCP experiences and provide policy makers and stakeholders with accurate data. Russia, which has the most extensive experience of NDH, should be more involved in international cooperation programs on nuclear cogeneration. These clusters should invite non-nuclear stakeholders, such as DH operators, to the debate. Last but not least, academicians should explore the social, political, institutional and financial aspects of NCP, thus allowing discussions to take a step back from purely technical aspects.

Despite not being excess heat recovery projects in the sense of Directive 2009/72/EC, we advocate that NCP should be recognized by the EC alongside other utilities generating large amounts of wasted heat. Furthermore, an effective carbon pricing system should be implemented. EU28 Member States wanting to promote NDH may consider opening DH networks to third-party access. Another option, perhaps more relevant, is providing support for the electricity generated by high-efficiency NCP.

It has been shown that, without adequate EU energy policies and EU28 Member State support, the potential of NCP will continue to be underestimated. We encourage the EU and its members to seriously consider the deployment of NCP with PWRs as a strategic pathway toward a sustainable EU energy system. The factors that could act as levers are: energy efficiency, decarbonization of the heat sector, independence from imported fossil-fuels, synergies between nuclear and renewable energies, and strategic considerations with regards to future nuclear technologies. Nonetheless, our study relies on a single case so caution is needed when applying the results to other contexts, but majority of the relevant influencing factors are presented. The fact remains that the overall assessment of NCP remains is to be done on a case-by-case basis and both from an environmental and economic point of view.

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Appendix A

Here Table A.1.

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Figure 1: Heat transportation system routing from the Loviisa 3 NDH unit to the Helsinki metropolitan area, about 80 km long. Data sources: ISNP, 2014.

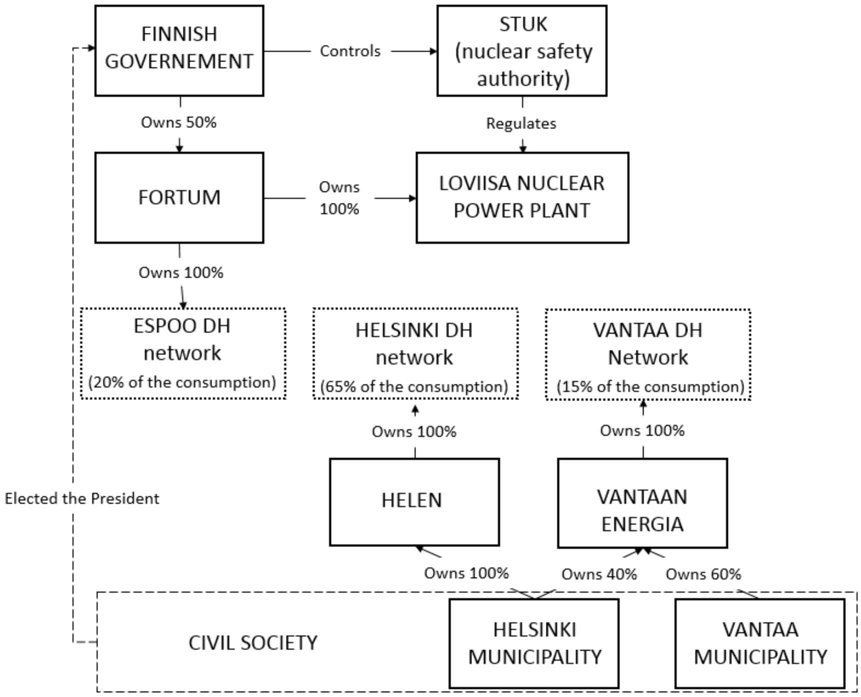

Figure 2: Current configuration of stakeholders involved in the Loviisa NPP and the Helsinki metropolitan area DH networks. Data sources: authors. With dotted line we have shown the DH networks. By dashed line we have reported the electoral process (including all the Finnish citizens).

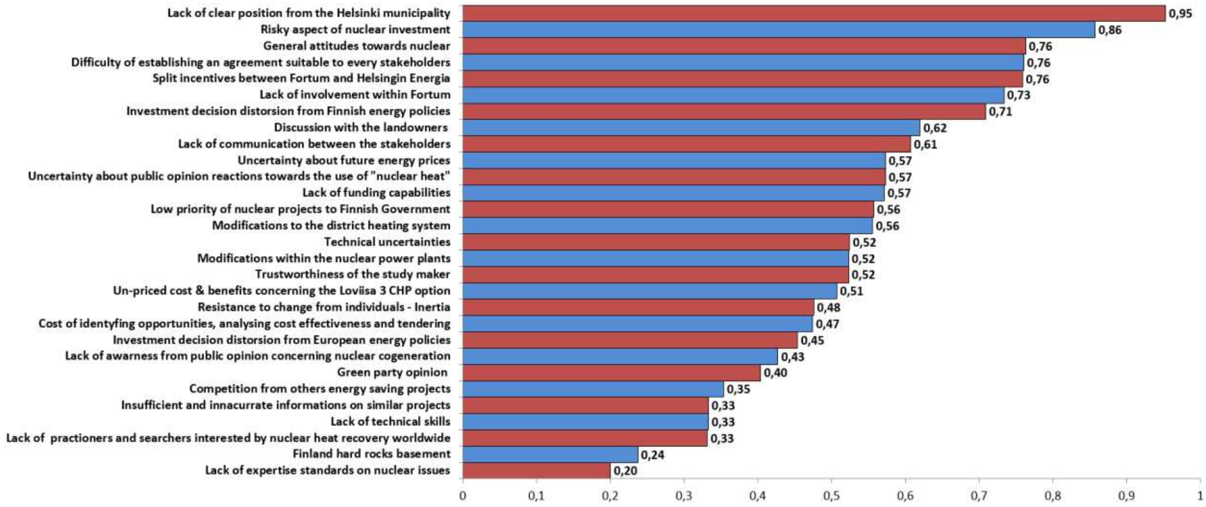

Figure 3: Obstacles to the Loviisa 3 Nuclear District Heating projects as perceived by Fortum respondents (10 out of 27). Respondents were asked to rank the obstacles to the Loviisa 3 NDH project as “Always important (=1); often important (=0.66); sometimes important (=0.33); never/seldom important (=0).

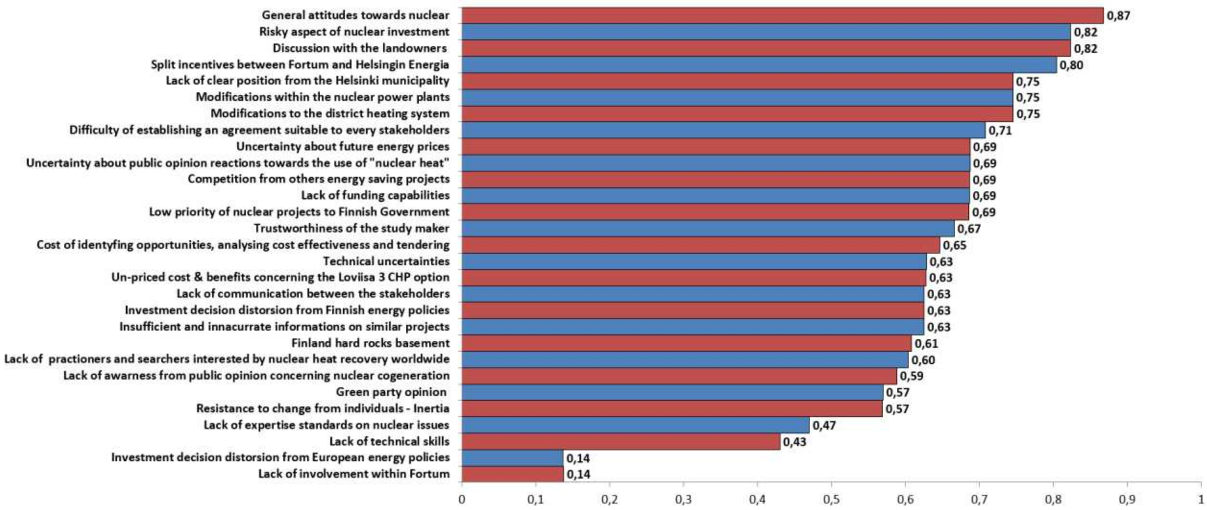

Figure 4: Obstacles to the Loviisa 3 Nuclear District Heating project as perceived by VTT respondents (17 out of 27). Respondents were asked to rank the obstacles to the Loviisa 3 NDH project as “Always important (=1); often important (=0.66); sometimes important (=0.33); never/seldom important (=0).

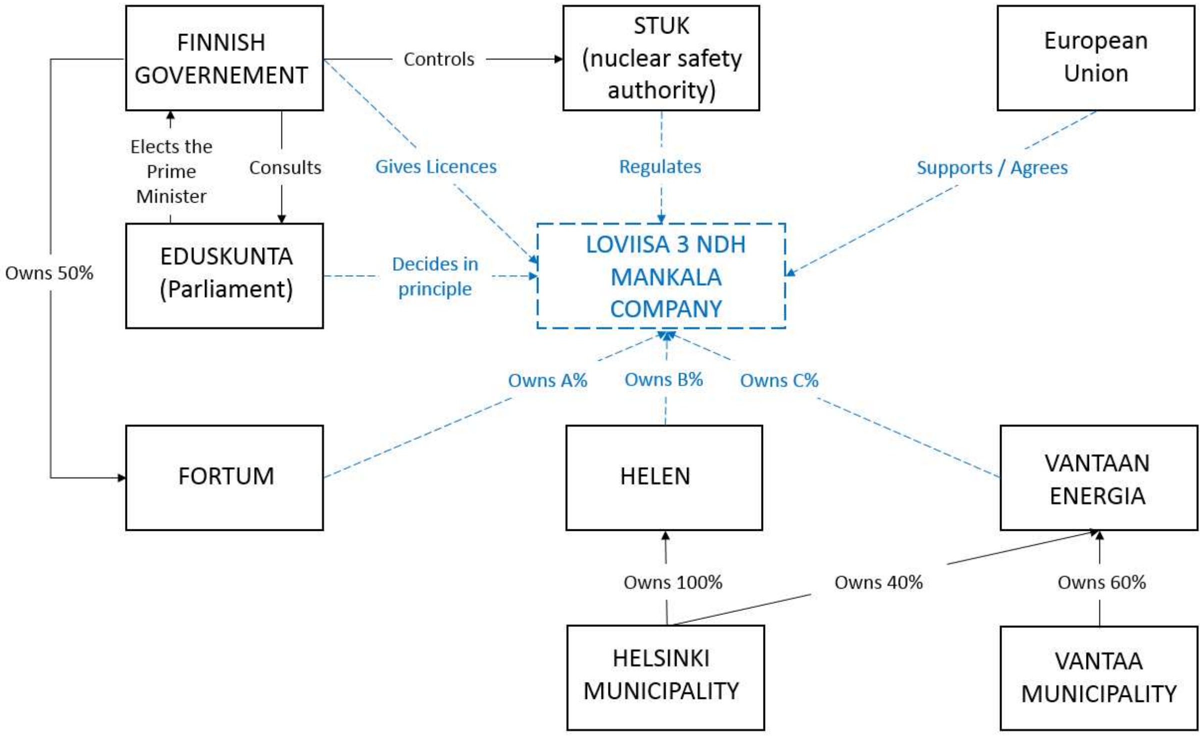

Figure 5: Theoretical project governance of a sustainable Loviisa 3 NDH project. Data sources: authors. With blue dashed line we have sketched: Theoretical processes surrounding the hypothetical Loviisa 3 NDH Mankala Company. As additional assumption: A + B + C = 100% (i.e. there are only three owners of the Mankala company).

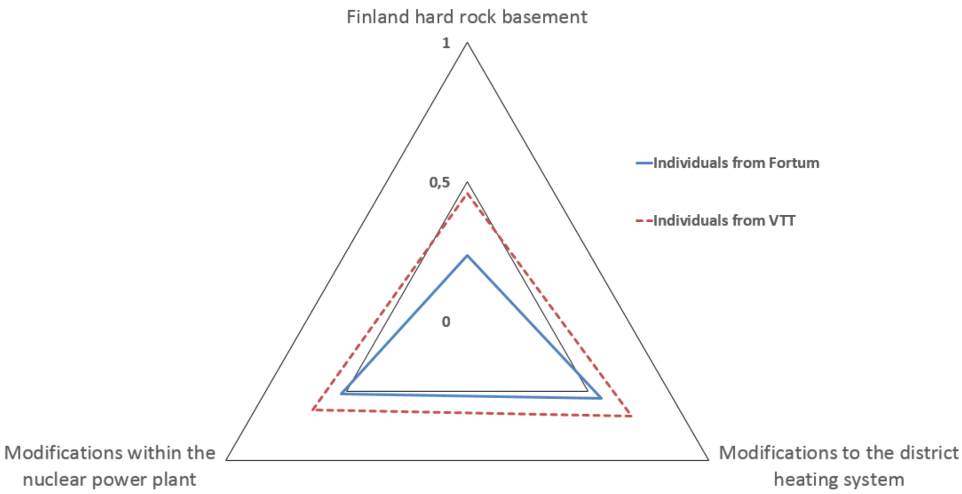

Figure 6: Importance of physical constraints on the Loviisa 3 NDH project, as perceived by individuals from Fortum and VTT respectively. Data sources: Authors.

Country	NCP name and reactor number	Location	Length of main pipe (km)	Start operation reactor	Power output (MWe)	Thermal output (MWth)	Temperatures (C°)
Bulgaria	Kozlodoy 5, 6	Kozlodoy	5	1987-91	2×953	2×20	150-70
Czech Republic	Temelin 1, 2	Tyn	5	2002	963	2×180	*Unknown*
Hungary	Paks 2, 3, 4	Paks	6	1983-87	3×433	3×30	130/70
Romania	Cernavoda 1	Cernavoda	2	1996	1×660	1×19	150-70
Russia	Bilibino 1-4	Bilibino	3.5	1974-81	4×12	4×47	150-70
	Novovoronezh 3, 4	Novovoronezh	50	1972-73	2×385	2×33	130/70
	Balakovo 1-4	Balakovo	12	1986-93	4×950	4×200	130/70
	Kalinin 1, 2	Udomlya	4	1985-87	2×950	2×80	128-70
	Kola 1-4	Apatit	64	1973-84	4×410	4×25	130/70
	Beloyarsk 3	Zarechny	-	1981	1×460	1×170	130/70
	Leningrad 1-4	St-Petersburg	5	1974-81	4×925	4×25	130/70
	Kursk 1	Kurchatov	3	1977	1×925	1×128	130/70
	Kursk 2-4	Kurchatov	3	1979-86	3×925	3×175	130/70
	Smolensk 1-2	Desno-gorsk	5	1983-1990	2×925	2×173	130/70
Slovakia	Bohunice 3, 4	Trnava	18	1985-87	2×410	2×240	150/70
Switzerland	Beznau 1, 2	Döttingen	35	1969-83	2×365	2×80	130/70
Ukraine	Rovno 1, 2	Rovno	4	1982	2×400	2×58	130/70
	Rovno 3	Rovno	4	1987	1×950	1×233	130/70
	South Ukraine 1, 2	Yuzhnoukrainsk	3	1976-83	2×950	2×151	150/70
	South Ukraine 3	Yuzhnoukrainsk	3	1976-89	1×950	1×232	150/70
	Zaporozhye 1-6	Energodar	5	1985-96	6×950	6×232	-

Table 1: Worldwide experiences in nuclear district heating. Data sources: IAEA, private communication; IAEA, 2002.

Notes: Reactors are all generation II reactors, mostly PWRs and WWERs (Water-Water Energetic *Reactor)*

Fortum	Helen
Replacement of heat generated with fossil fuels	Cost for produced and transferred nuclear heat is higher compared with local heat production
Large reduction of carbon dioxide emissions (6% of the entire emissions in Finland)	A full back-up capacity for heat production is needed (technical and political risk)
Higher plant efficiency	Nuclear cogeneration does not increase electricity generation when replacing current cogeneration in Helsinki area
Steam extraction from the turbine (technically feasible)	Nuclear district heat is not renewable energy

Table 2: Mains arguments exposed by Fortum and Helen respectively when addressing nuclear district heating for the Helsinki area. Data sources: Helen Ltd (2015b); ISNP (2014).

Stakeholder	**Field**	**Function**	**Complementary sources**
Nuclear Plant Operator (Fortum)	Power Division	Senior Nuclear Safety Officer	Conference papers and corporate reports
Nuclear Plant Operator (Fennovoima)	Nuclear Engineering	Manager *Notes: Co-lead the Loviisa 3 NDH feasibility study in 2009 as a Fortum employee*	Research paper
Helsinki District Heating network operator (Helen)	Energy Business Development	Head of Unit	Corporate reports
	Energy Development and Wholesale	Vice-President	Corporate reports
Ministry of Employment and the Economy (TEM)	Energy Department	Cogeneration expert	National Energy and Climate Strategy, TEM, 2013
Radiation and Nuclear Safety Authority (STUK)	Design of a nuclear power plant, systems and structures	Expert on nuclear power plant safety	Technical reports
City of Helsinki Environment Center	Environmental Protection Department	Environmental Inspector	Helsinki Climate Roadmap 2050
Environmental Committee of Helsinki	Politic	Deputy of Social Democrat Party	Political reports and newspapers
Technical Research Center (VTT)	Reactors Physics	Principal Scientist	NC2I reports
	District Heating	Principal Scientist	PhD Report
	District Heating	Research Scientist	Informal discussions
	Energy Systems	Research Team Leader	Informal discussions
	Energy Systems	Senior Scientist	Informal discussions
	Energy Systems	Senior Scientist	Technical reports
	Process Engineering and Sustainability	Senior Scientist	Technical reports

Table A.1: Details of the semi-structured interviews. All interviews were conducted in 2015.