Model reaplikacije za planiranje, razvoj i integraciju pametnih centraliziranih toplinskih sustava u pametne energetske sustave

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MASTER'S THESIS

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Zagreb, 2016.

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ACKNOWLEDGEMENTS

This thesis was carried out under the collaboration with the Sustainable Energy Planning research group, a part of the Department of Development and Planning at Aalborg University – Copenhagen Branch in Denmark and Faculty of Mechanical Engineering and Naval Architecture at University of Zagreb. The thesis contributes to the Horizon 2020 project, SmartEnCities, and the two research projects supported by Innovation Fund Denmark: 4DH – an International Research Centre of 4th Generation District Heating [1], as well as the Center for IT - Intelligent Energy System in Cities (CITIES). I wish to express gratefulness to the following people for supervising me, giving me insights and advices, supporting me and for making all of this possible.

First of all, I would like to thank my supervisors, Professor Brian Vad Mathiesen and Assistant Professor Goran Krajačić for all the useful feedback they provided me during the making of this thesis. I would also like to thank them for making my stay at Aalborg University as a part of Erasmus internship possible in the first place.

Big thanks also goes to Assistant Professor Iva Ridjan, research assistant Dave Drysdale and PhD fellow Kenneth Hansen for giving me clarifications when needed during my stay at Aalborg University.

At last, I would like to thank my parents Neda and Damir, my aunts Vera and Mirjana as well as my girlfriend Tajana for always being the biggest support in my life, in both good times and in difficult times.

I hereby declare that this thesis is entirely the result of my own work except where otherwise indicated. I have fully cited all used sources and I have only used the ones given in the list of references.

Borna Doračić

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Naslov rada na hrvatskom jeziku: **Model reaplikacije za planiranje, razvoj i integraciju pametnih centraliziranih toplinskih sustava u pametne energetske sustave**

Naslov rada na engleskom jeziku: **Reapplication model for planning, development and integration of Smart district heating systems in Smart energy system**

Opis zadatka:

Cities are among the most important assets in Europe today in which more than 70 % of the EU-28's population lives, which are drivers of Europe's economy and which are responsible for a significant percentage of CO_2 emissions. There are big potentials for energy savings in cities and therefore, cities are supposed to play a key role in fighting climate change. Today, there are a number of cities in EU that are leading the way in the transition towards a low carbon intensity and resource-efficient economy and there are projects which aim to develop and demonstrate a highly adaptable and replicable systemic approach towards urban transformation into sustainable, smart and resource-efficient urban environments in Europe. Transformations take place in different energy sectors including transport, electricity, heating etc.

In the thesis it is necessary to complete the tasks outlined below:

a. Comprehensive review of Smart cities projects database, Literature and web pages in order to identify lessons learned from ongoing demonstration activities in Smart Cities and provide synthase that will form input data to Work package 8 of project SmartEnCities.
b. Analysis of the ways and strategies for matching the experience of lighthouse cities to the follower cities and identifying necessary requirements cities should have or follow for successful replication (region-specific, problem-specific, societal norms and cultural elements etc.)
c. Identify main characteristic of DH system in Smart energy system and audience of SmartEnCity project "who, what, when, where, why and how"
d. Draft the Reapplication flowchart and main features of Individual reapplication plan for Smart district heating systems in Smart energy system of SmartEN City project
e. Identify and discuss at least three available tools that will be used during the implementation of replication and scaling-up plans in the city of Sønderborg.
f. Propose content of Individual reapplication Roadmap for Smart District heating systems of the city of Sønderborg

Necessary data and literature could be obtained from the supervisors. In the thesis, it is also necessary to state used literature and received help.

Zadatak zadan:	Rok predaje rada:	Predviđeni datumi obrane:
12. studenog 2015.	14. siječnja 2016.	20., 21. i 22. siječnja 2016.

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ABBREVIATIONS

CAD	Computer Aided Design
CHP	Combined Heat and Power
DH	District Heating
DHW	Domestic Hot Water
DSM	Demand Side Management
DXF	Drawing Exchange Format
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information System
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communications Technology
RE	Renewable Energy
RES	Renewable Energy Sources
SCADA	Supervisory Control And Data Acquisition
SET	Strategic Energy Technology

SUMMARY

This thesis deals with replicating smart district heating systems as a part of smart energy systems in smart cities. The thesis was done done with inspiration from the Workpackage 8 of SmartEnCity EU research project and the municipality of Sønderborg, Denmark.

First, a brief review of smart cities and smart district heating projects was carried out in order to define important lessons learned from ongoing demonstration activities to serve as a valuable input in SmartEnCity project.

Description of smart district heating systems, defining their main characteristics was given by means of comprehensive review of existing literature. In order to replicate a smart district heating system from one city to another, it is necessary to define important aspects for replication. Main aspects that were defined and explained are geographical, financial, technical and ownership aspects.

After defining important aspects for replication, important steps of methodology for replication of smart district heating systems are defined and described and the replication flowchart is drafted giving a step-by-step graphical representation of the methodology.

Finally, four tools to be used in replication activities in the city of Sønderborg were defined and described and also the content for individual replication in the city of Sønderborg was proposed.

Key words: smart district heating system, replication, smart city, methodology, Termis, energyPRO, NetSim, I.H.E.N.A., C.a.R.D.I.F.

SAŽETAK

U ovom radu obrađena je tema reaplikacije pametnih centraliziranih toplinskih sustava kao dijela pametnih energetskih sustava u pametnim gradovima. Rad je napravljen u skladu s zadacima postavljenima u radnom paketu 8, projekta SmartEnCity.

Najprije je proveden sažeti pregled projekata pametnih gradova i pametnih centraliziranih toplinskih sustava kako bi se odredili važni podaci iz projekata u tijeku. Dobiveni podaci će služiti kao vrijedan doprinos u SmartEnCity projektu.

Opisom pametnih centraliziranih toplinskih sustava su definirane njihove glavne karakteristike. Opis je dan uz pomoć sveobuhvatnog pregleda postojeće literature.

Kako bi se pametni centralizirani toplinski sustav kopirao, tj. replicirao iz jednog grada u drugi, potrebno je odrediti važne aspekte za replikaciju. Glavni aspekti koji su definirani i objašnjeni su: geografski, financijski, tehnički i aspekt vlasništva.

Nakon definiranja važnih aspekata za replikaciju, definirani su i opisani važni koraci metodologije za replikaciju pametnih centraliziranih toplinskih sustava, te je izrađen dijagram toka replikacije dajući grafički prikaz metodologije, korak po korak.

Konačno, definirana su i opisana četiri alata za korištenje u svrhu replikacije aktivnosti u gradu Sønderborg. Također, predložen je i sadržaj plana djelovanja za individualnu replikaciju u gradu Sønderborg.

Ključne riječi: pametni centralizirani toplinski sustav, reaplikacija, pametni grad, metodologija, Termis, energyPRO, NetSim, I.H.E.N.A., C.a.R.D.I.F.

PROŠIRENI SAŽETAK (EXTENDED SUMMARY IN CROATIAN)

Ovaj rad je podijeljen na šest poglavlja. U prvom poglavlju, koji predstavlja uvod, napravljen je pregled literature vezano uz područja pametnih gradova, pametnih energetskih sustava te pametnih centraliziranih toplinskih sustava. U ovom poglavlju su također prikazani projekti pametnih gradova kako bi se moglo utvrditi što se može naučiti iz danih projekata.

Prikazana su tri projekta pametnih gradova, u Amsterdamu te u dva grada u Brazilu (Águas de São Pedro i Porto Alegre). Iz prikazanih rezultata danih projekata može se zaključiti da je osiguravanje političke potpore jedan od najvažnijih koraka u provedbi ideje pametnog grada, kao i da je uključenost stanovnika u projekt od iznimne važnosti te da je potrebno jasno odrediti ulogu svih sudionika u projektu.

U drugom poglavlju rada definirano je trenutačno stanje centraliziranih toplinskih sustava u Europi, kao i karakteristike pametnih centraliziranih toplinskih sustava. Prednosti centraliziranih toplinskih sustava su: smanjenje zagađenja okoliša te bolja kvaliteta zraka, efikasno iskorištavanje energije, stabiliziranje troškova energije i dobave, manji sigurnosni rizici u zgradama, povećana iskoristivost prostora u zgradama, itd.

Glavne karakteristike pametnih centraliziranih toplinskih sustava se mogu sažeti kako slijedi: korištenje obnovljivih izvora energije za proizvodnju topline čime se potiče distribuirana opskrba; iskorištavanje niskotemperaturne otpadne topline iz industrije, korisnika itd.; korištenje niskotemperaturnog sustava sa temperaturom polaza 50 ºC, a povrata 20 ºC; korištenje dizalica topline velike snage i skladištenja topline (pomoću kratkoročnih i/ili sezonskih spremnika topline) u svrhu balansiranja mreže električne energije; korištenje kaskadnih sustava kako bi se visokotemperaturni centralizirani toplinski sustavi integrirali sa niskotemperaturnima; korištenje novih materijala za cijevi (poput savitljivih plastičnih cijevi) čime se smanjuje cijena cijevi i ugradnje; korištenje nerazornih metoda održavanja i ugradnje cijevi; korištenje pametnih uređaja za mjerenje topline; te korištenje upravljanja potražnjom kako bi se smanjili dnevni vrhunci potrošnje topline.

U trećem poglavlju su definirana četiri najvažnija aspekta bitna za kopiranje pametnih centraliziranih sustava u druge gradove. Radi se o geografskom aspektu, tehničkom aspektu, financijskom aspektu i aspektu vlasništva. Geografski aspekt je podijeljen na klimatski aspekt, zgrade Europe i potencijale za obnovljive izvore energije.

Naznačena je potreba za mapiranjem lokalnih toplinskih potreba i potencijala obnovljivih izvora energije u procesu planiranja centraliziranih toplinskih sustava te su dani primjeri mapiranja na razini Europe.

Tehnički aspekt je podijeljen na određivanje trenutnog stanja sustava grijanja, mapiranje viška topline te spremnike topline. Objašnjene su karakteristike vrsta spremnika topline koji će se koristiti u pametnim centraliziranim sustavima, nužnost mapiranja viška topline i izvori viška topline te kompliciranost implementacije pametnog centraliziranog toplinskog sustava ovisno o trenutnom stanju sustava grijanja u gradu.

Financijski aspekt je podijeljen na isplativost sustava i financiranje sustava. U pogledu isplativosti sustava, mora se uzeti u obzir isplativost izgradnje pametnog centraliziranog toplinskog sustava kao i isplativost provođenja mjera energetske učinkovitosti u zgradama. Dvije vrste troškova postoje kod pametnih centraliziranih toplinskih sustava, a to su troškovi proizvodnje topline i troškovi distribucije topline no njihov zbroj je svejedno manji od individualnih rješenja čiji se troškovi sastoje samo od troškova proizvodnje topline.

U pogledu isplativosti provođenja mjera energetske učinkovitosti u zgradama, može se zaključiti da je isplatljivo samo ako se zgrada ionako obnavlja, ili pri izgradnji novih zgrada. Za financiranje ovakvih projekata potrebno je definirati fondove koji mogu pokriti dio troškova poput Regionalnog i Razvojnog Fonda i uz potporu Europske Investicijske Banke.

Aspekt vlasništva se odnosi na vlasništvo nad centraliziranim toplisnkim sustavom te na vlasništvo nad zgradama. Vlasništvo nad centraliziranim toplinskim sustavima može biti javno, privatno ili privatno-javno partnerstvo. Nema točnih indicija koji način je najbolji, bolje rečeno to ovisi o uvjetima u svakom gradu, ali u novije vrijeme najviše sustava koristi prednosti privatno-javnog partnerstva.

Vlasništvo nad zgradama ima veliki utjecaj na odluku o provođenju mjera energetske učinkovitosti te se razlikuje u različitim dijelovima Europe.

U četvrtom poglavlju su definirani glavni koraci metodologije za kopiranje pametnih centraliziranih toplinskih sustava. Svaki korak je objašnjen te je na kraju predložen dijagram toka za replikaciju.

Glavni koraci su: dobivanje političke potpore, organizacija prvih mjera i izrada prve verzije plana, mapiranje svih sudionika, skupljanje informacija, analiza informacija, analiza dobre prakse, prijedlog mjera, određivanje financijskog okvira i prijedlog plana implementacije te implementacija.

Za kraj, u petom poglavlju dan je opis četiri alata za korištenje u svrhu replikacije aktivnosti u gradu Sønderborg: NetSim, energyPRO, Termis i I.H.E.N.A./C.a.R.D.I.F. Također, predložen je sadržaj plana djelovanja za individualnu replikaciju u gradu Sønderborg.

Sadržaj uključuje uvodni dio, procjenu trenutnih lokalnih uvjeta, procjenu mogućih prepreka za replikaciju, utvrđivanje nužnih potreba za provedbu replikacije, popis rješenja koja se mogu implementirati u ostatku grada, utvrđivanje glavnih događaja tijekom procesa replikacije te određivanje financijskog plana koji će osigurati replikaciju inovativnih rješenja.

1. INTRODUCTION

In todays society, GHG (greenhouse gas) emissions represent a significant problem due to their effect on climate change and its steadily increasing rate. When talking about GHG emissions, CO_2 emissions represent the biggest share since the majority of world is still driven by non-renewable fossil fuels. Urban areas are contributing significantly to climate change and it is estimated that around 75 % of global CO_2 emissions come from cities with the biggest share from transport and building sector [2]. Cities are of utmost importance in todays society. When looking at EU, almost three quarters of EU-28's population lives in built-up areas (cities, towns and suburbs) [3] and around 85 % of GDP is generated in cities [4].

However, urban density enables cities to implement more energy-efficient forms of housing, transport and service provision and makes energy efficiency measures more feasible and efficient which shows that cities actually have a key role in fighting climate change.

In [5], authors have discussed climate change and importance of cities in dealing with climate change, concluding that current independent efforts by cities, consumers and business to slow down climate change will not suffice and presenting a tri-partite model for sustainability programs (including three stakeholders – cities, consumers and business). It recognises that smart energy systems will have a great role in transforming cities into sustainable, low carbon environments.

The smart energy system is an energy system concept which is based on a 100 % renewable energy. Important part of an energy system is energy production. There are two main forms of energy production in a smart energy system: bioenergy and intermittent renewable energy. Concerning the bioenergy, a lot of its characteristics are alike fossil fuel characteristics, making it an acceptable replacement for fossil fuels. The main problem with bioenergy is that it will be a scarce resource in the future systems while the main problem of intermittent renewable energy is the intermittency itself.

To accomodate large amounts of intermittent renewable energy and ensure the sustainability of biofuels it is necessary to achieve synergies between the electricity, heat and transport sector by utilizing especially thermal storage, heat pumps, electric vehicles, electrofuels and fuel storage. That way, the flexibility across these different sectors compensates for the lack of flexibility of intermittent renewable energy.

Therefore the smart energy system can be divided into 3 main grid infrastructures: *smart electricity grids* which connect flexible electricity demands such as heat pumps and electric vehicles to the intermittent renewable resources such as wind and solar power; *smart thermal grids* which connect electricity and heating sectors; *smart gas grids* which connect the electricity, heating, and transport sectors enabling utilization of gas storage, which creates additional flexibility.

The smart energy system results in 100 % renewable energy system and zero net CO_2 emissions and it is based on domestic structure which helps creating more local jobs [6]. The concept of smart energy system is presented in Figure 1.

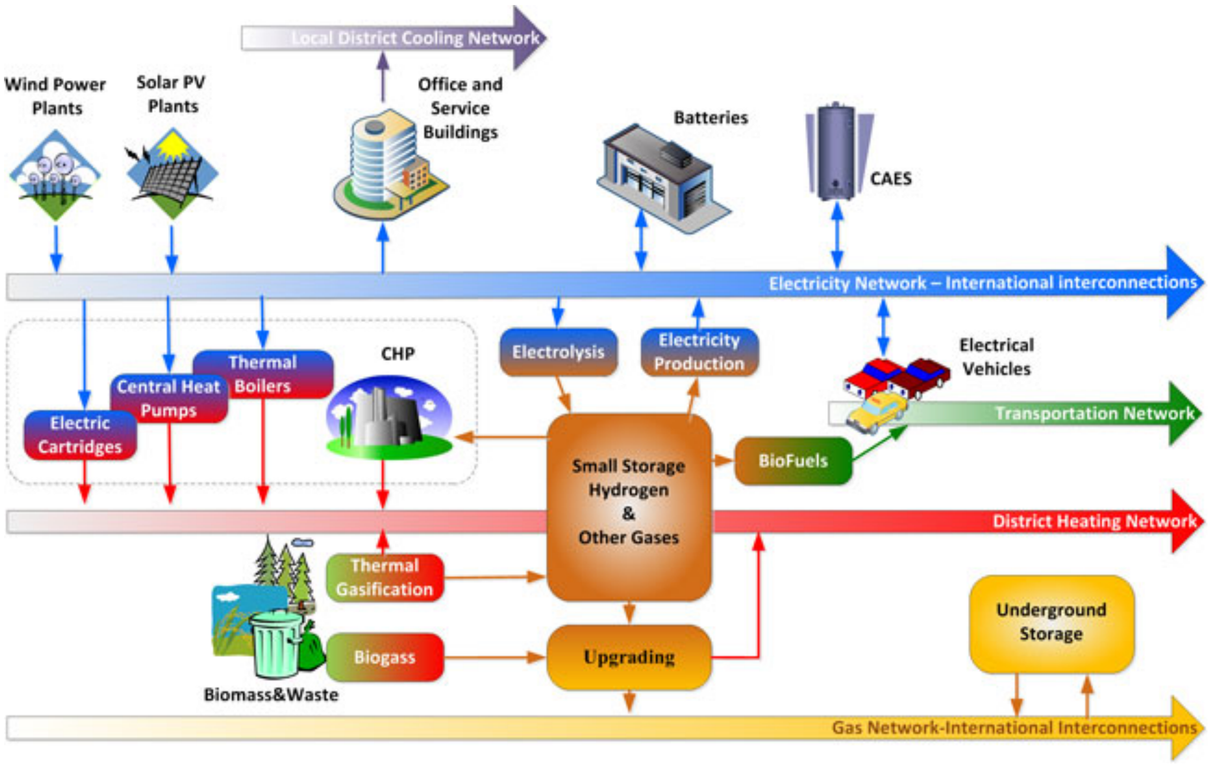

Figure 1. The concept of smart energy system [7]

Increasing the amount of renewable energy over the self-use limit requires smarter strategies and the smarter design of the system as shown in [8] for the case of three different cities including Helsinki. Authors concluded that integration of RES with smart electricity grids and thermal storages in the city of Helsinki helps increase yearly RES share of power production from around 30 % (short-term electricity storage case) to 64%, which is a significant increase.

Instead of focusing on one sector or one technology at a time, it is necessary to analyse all sectors of energy system taking into account equal importance of many technologies as discussed in [9]. This way, integrating different parts of energy sector makes a fuel efficient and cost effective option, although it is necessary to understand, as concluded in [9] that design and layout of the system have to be carefully planned in order to achieve feasible solution.

Regarding the increased cost effectiveness when using the smart energy management, the study was carried out in [10] focusing on integration of transport (electric vehicles plugged in to smart grids) and thermal storage and concluding that smart energy management reduces costs significantly.

This thesis will be concerned with the heat sector – smart district heating network, its implemetation in a smart city and replication of such a system to other cities. The present and future (smart) state of district heating systems will be discussed in detail in Chapter 2.

Some of the main aspects of smart district heating systems are low distribution temperatures, utilisation of RES and thermal storage. These aspects have been covered by many papers. The future district heating systems are also being called 4th generation district heating systems and they should include providing the heat supply of low energy buildings with low grid losses so that using low temperature heat sources incorporates the operation of smart grid systems [11]. The proposed temperature levels in [11] are 50 ºC supply temperature and 20 ºC return temperature as annual averages.

Furthermore, as shown in [12] on example of 4 houses in Birkeroed, Denmark that an ultra low temperature district heating system (supply temperatures below 45 ºC) with microboosters can be implemented resulting in summer supply temperature of 30-35 ºC (for new buildings it could be during the whole year) which reduces heat losses by 30-40%, allows very efficient use of low temperature and RES and maintains the same comfort for the users. DHW was taken into account by microboosters that prevent legionella dissemination by heating DHW at substations.

In [13] it was shown that, on the case of West Sweden, the collaboration between DH systems and industry (excess heat) would be cost-efficient under most scenarios (although results are sensitive to assumptions of the development of the DH system and the additional pipeline cost) but has also shown that the environmental impact is highly case sensitive, depending on the DH fuels excess heat substitutes and the amount of CHP in the system.

Concerning the cost-effectiveness of DH system over the individual heating, in [14] authors compare the price of district heating technologies (for the systems with multiple heat sources-gas and RES) and individual heating technologies, concluding that for the city areas, district heating with multiple heat sources is a much more cost effective way (and more environmentally friendly) for heating and has a bright future.

In [15] authors simulate the profit of the CHP plant in 3 different thermal storage scenarios: with the central buffer, without the buffer-thermal mass of the buildings is used as a distributed thermal storage and with smaller distributed buffers along with thermal mass of the buildings.

They concluded that all this cases increased the profit of the CHP compared to a system without thermal storage but that the distributed buffers scenario gave better performance than single buffer scenario. Active control can be very profitable for future district heating systems.

Reductions of GHG emissions in cities due to DH systems are already significant. For example, Tokyo emits 50 % less CO_2 due to DH then it would with individual heating options, Gothenburg CO_2 emissions reduced by 50 % from 1973 due to DH. In Copenhagen, recycling waste heat for use in DH systems results in 655 000 t annual reductions of CO_2 while in Paris it results in 800 000 t of annual CO_2 reductions. It is expected that if smart district energy (including cooling) solutions, along with energy efficiency measures are implemented, it can contribute to up to 58 % of required CO_2 reductions that should be achieved by 2050 in the energy sector in order to keep global temperature rise to within 2-3 ºC [16].

Although, no city has yet fully incorporated the smart energy system concept, there are some smart energy city projects with demonstration activities that can help other cities by presenting the lessons learned.

In Netherlands, Amsterdam Smart City project has been carried out that lasted two years [17]. Some of the technologies considered in this project were distributed generation, energy storage, smart meters, smart lighting, electric vehicles etc. Some of the main lessons learned are as follows. Since the end user and his behavior control the energy use, it is necessary to engage them to become actively involved in energy savings but is also necessary to have ready-to-use solutions so that the user isn't burdened with technological complications. Standardization of smart meters and interface of technologies has showed crucial for implementation of smart energy systems. It was also noticed that only highly motivated businesses and people are trying to reduce energy usage and GHG emissions and therefore local government should pass strict regulations to increase motivation.

Another project was carried out in Brazil with a "living lab" cities of Águas de São Pedro and Porto Alegre [18]. One important conclusion of the project is that it is extremely important to have a visionary leader in the City Hall, someone in the government with a vision who is responsible for the initiative, and also it is necessary to have the support and commitment of all involved areas inside City Hall. Furthermore, the roles of each participating company in implementation of smart energy cities should be clearly defined as well as the expected results. In this project, the role of citizens is also emphasized (involment and feedback from citizens) as it was in the Amsterdam Smart City project which shows how important it is to have the citizens included during the implementation of smart energy systems. It should be emphasized that those projects, although claiming to be smart energy projects mostly concentrate on smart electricity grids and neglect other aspects of a smart energy system. This was noticed in the majority of smart energy projects that were encountered during literature overview.

There is also an ongoing project of developing advanced DH systems and improving the existing systems in 45 lighthouse cities over the world. High emphasis is on utilisation of RES, enabling 11 of the 45 champion cities to have 100 % renewable energy or carbon-neutral targets for all city sectors. Local governments were ranked as the most important stakeholder by all the cities in the project in catalyzing investment in district energy systems. Integrated energy planning and mapping recognised as a best practice to identify synergies and opportunities for cost-effective district energy systems, and to apply tailored policies or financial incentives [16].

Additional best practices that were identified in the project are: CHP access to the retail electricity market; net metering policies and incentives for feed-in of distributed generation; customer protection policies, including tariff regulation; technical standards to integrate multiple networks; and cooperation with neighbouring municipalities for joint development or use of networks. When it comes to business models, it was pointed out that technically and financially replicable as well as scalable business models are key to the acceleration of the district energy. Also, in order for district energy systems to benefit from local expertise and the influence and action of local authorities authority should be devolved from national level to local authorities [16].

The research question of this thesis could be defined as: what defines a smart district heating system, how can those systems be implemented across different European cities and what are the main aspects that are important for replicating such systems in different cities.

The thesis will describe state-of-the-art smart district heating systems, identifying the main characteristics of such system. In order to define the steps for replication of smart DH systems in different cities, important aspects for replication will be defined and explained.

Aspects that are going to be taken into account are geographical aspects, financial aspects, technical aspects and ownership aspects. After the definition of aspects, a methodology for implementation of smart DH system is going to be proposed consisting of two parts, preparation (planning) and implementation after which the replication flowchart will be drafted. Methodology will be made generally for cities in Europe. This thesis will also give a brief analysis of different tools that can be used for replication planning and implementation of smart DH systems.

2. SMART DISTRICT HEATING SYSTEMS – PRESENT AND FUTURE STATE

Even though there are over 7000 district heating systems in Europe, they are unequally distributed throughout countries with some countries having no DH systems and other countries with shares above 60 % [19]. The overall share of district heating systems in Europe is above 10 % of total European heat demand with big potentials to expand since heat demands in urban areas are dense enough to utilise DH systems. Some countries have rather outdated DH systems that are pretty inefficient while other countries (with the focus on Nordic countries) are leading the way towards new, smart DH systems.

Future DH systems are also called 4th generation district heating systems [11]. Smart DH systems will have a significant role in future energy systems, supplying reliable and affordable heating to customers by utilising RES such as solar thermal, biomass, waste incineration, waste heat, geothermal sources etc. and they will enable adapting to various changes in heat supply and demand and also interaction with end-users (where consumers can also be producers, hence they are called prosumers). Smart DH systems will have to be integrated with other sectors into a whole, making a smart energy system. Some other important characteristics that the future smart DH systems should have are flexibility, competitiveness, efficiency, intelligence and scalability [19]. Another extremely important aspect of smart DH systems is integration of thermal storage with both heating and electricity sector. The concept of smart DH network as a part of smart energy systems is shown in Figure 2. In the next two subchapters, present and future, smart state of district heating systems will be presented.

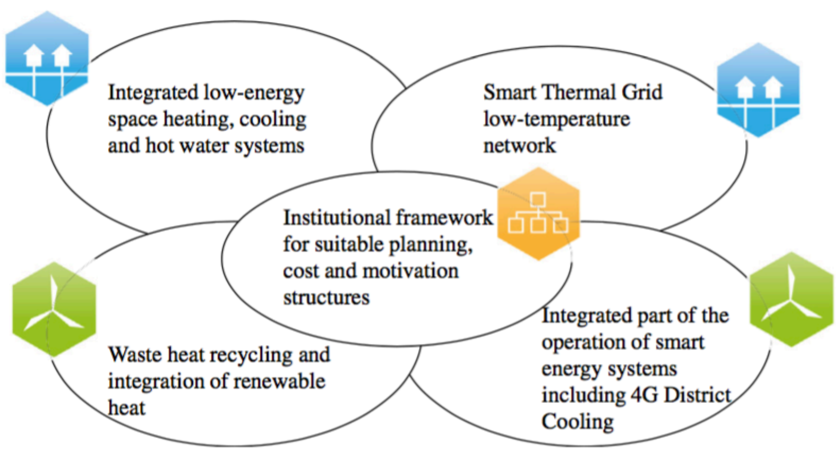

Figure 2. The concept of smart district heating system as a part of smart energy system [11]

2.1. Present state of district heating systems

In Europe, the most widespread DH systems are currently the 3rd generation systems (although there are still 1st and 2nd generation systems in existence) which include distribution of heat from a central source to individual customers by means of hot, pressurised water flowing through distribution pipes. Some of the older systems (1st generation) also use steam as a heat carrier. Heat from DH systems is mostly used for space heating and domestic hot water (DHW) but can also be used for low temperature industry needs.

The most used energy sources for DH systems in Europe today are surplus heat sources (i.e. heat that would otherwise be wasted) accounting for around 82 % of DH supply while RES (i.e. geothermal, solar, biomass and waste) account for around 14 % in the energy source mix. Main advantages of DH systems can be summed up as follows: reduction of environmental pollution and improvement of air quality, using energy more efficiently thus conserving scarce natural resources, stabilization of energy costs and supplies, increase of usable space in buildings and lower capital investment for the user, lower safety risks in buildings etc. [19] and [20].

Currently, the majority of production units for DH are combined heat and power units (CHP) that use the heat remaining from electricity production which would otherwise be wasted. Fuels used for CHP are predominantly natural gas, biomass and coal. It is important to note that production units mostly rely on a single feedstock as a fuel and therefore lack the flexibility when the prices or availability of fuels changes. This will have to be changed in the future by diversifying fuel supply to a mix of feedstocks. Some of the solutions for increasing diversified and balanced fuel mix include dual fuel options and bio-digestion options [19].

Besides the standard production units, a thermal storage can also be mounted, which is used in many networks for peak load reduction in terms of a water filled buffer. This type of storage represents the short-term storage and already, a lot of experience in design, production, integration and operation has been gained for future development. Temperature levels in current DH systems differ, depending on the generation of the system in use. When looking at different generations of DH systems, continuous decrease in distribution temperatures can be noticed in every new generation. The distribution temperatures have fallen from above 100 ºC for 1st and 2nd generation to temperatures noticeably below 100 ºC in 3rd generation systems [11].

Nevertheless, current temperature levels in most of the countries are still too high and in need of significant reduction. One of the barriers for reduction of distribution temperatures below 50 ºC is the legionella problem in DHW. The legionella bacteria multiply where temperatures are between 20-45 ºC and there are nutrients available. Some of the ways of dealing with this problem will be mentioned in the next subchapter. In the next figure (Figure 3) the development of DH system throughout generations is illustrated, regarding the distribution temperatures and technologies used.

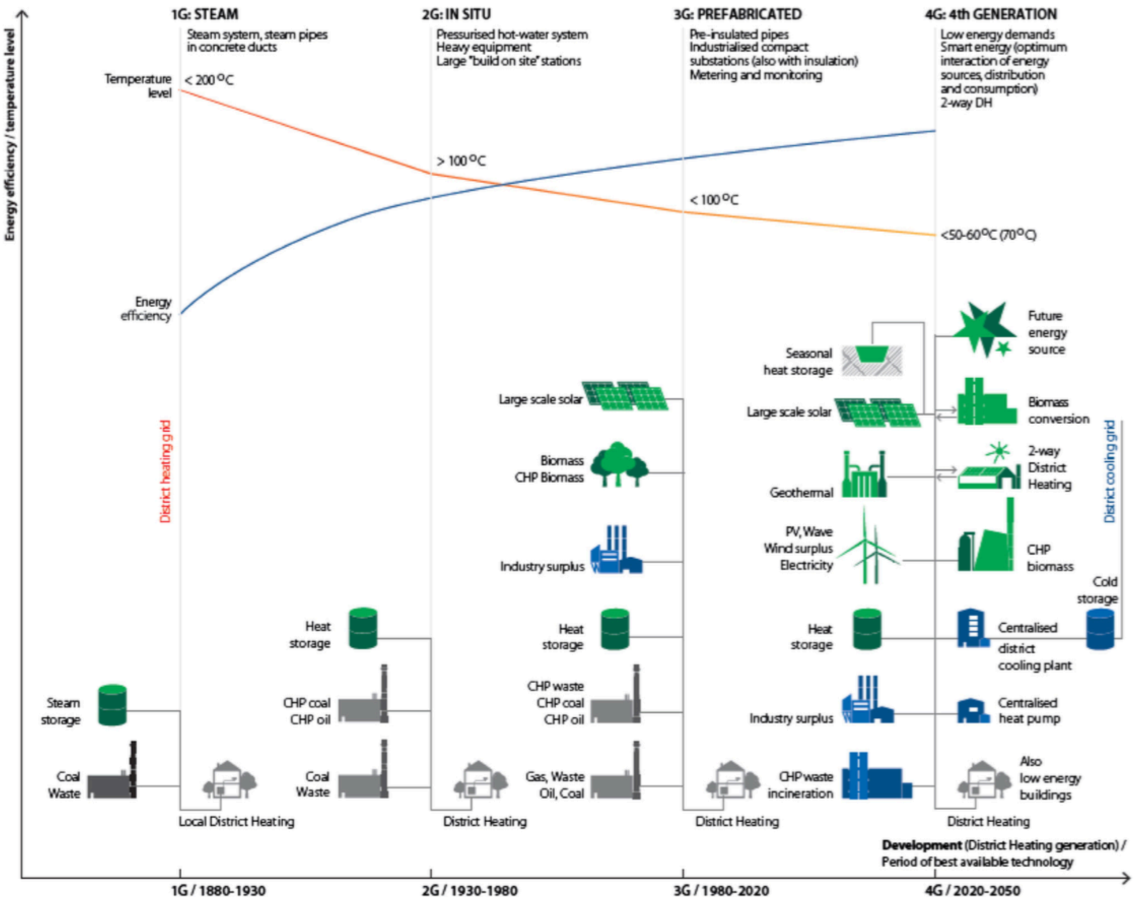

Figure 3. Development of district heating systems throughout generations [11]

Concerning the piping systems, most of the new pipes and substations are being hand-made (therefore they are expensive) and the design temperatures are above 70 ºC. One of the problems is installation technologies in use, which demand disruptive construction and maintenance works. Smart meter technology, although being thoroughly discussed in smart electricity grids, is currently not represented in thermal networks. Installation costs are pretty high, the meters themselves are relatively expensive and the legal barrier is also present (i.e. data security and privacy of the customer) [19].

2.2. Future state of smart district heating systems

There are currently no smart DH systems in the world but there are some rather advanced systems that incorporate some features of smart DH system. By analysing the literature, the most important characteristics of smart DH systems can be presented. As previously mentioned, heat sources for smart DH systems will be low-carbon and RES which means they will be locally available, stimulating a more distributed heat supply. There are various possibilities for RES like using geothermal heat, solar thermal or biomass to be utilized in CHP units. Also, the low temperature waste heat from processes in industry and commercial buildings along with heat produced locally by consumers (most often from renewable energy systems – e.g. solar collectors) should be utilized in smart DH systems.

Different RES use different technologies to convert them into heat or heat and power. Solid and liquid biomass can be converted to direct heat or heat and power by means of combustion and gasification. Thermal gasification is used to convert solid and liquid biomass to biomethane while anaerobic digestion is used to convert organic waste like animal manure, energy crops and sludge to biogas which can be used for combustion or can be upgraded into biomethane and injected into grid or used as a transport fuel. Landfill gas produced at a landfill site from food and fibre product residues can also be used for combustion [21].

Geothermal heat can be used directly for DH systems or by means of a heat exchanger when it can also be used for steam production which results in heat and power production. Collectors that can be used for solar energy utilisation are non-concentrating, low-concentrating and high-concentrating collectors with the first two giving direct heat while the last one can be used for heat and power production by the means of steam turbine.

One of the cost effective heating solutions for integrating DH systems with RE fluctuating electricity is by the means of heat pumps. This will also increase the level of feasible wind power in the electricity system. The market price for electricity determines which production unit will operate. If the price of electricity on the market is low, than the heat pump unit will operate consuming the cheap electricity and producing heat. Similarly, if the price of electricity on the market is high than the CHP unit will operate producing electricity (and heat as a byproduct) which will be sold with the high price on the electricity market [22]. Therefore, heat pumps can be used for balancing of the electricity network, along with thermal storage units.

Short-term thermal storage can use excess electricity from fluctuating RES to store it as heat. Although it does not generate electricity, it has a similar effect as a battery since it uses electricity to heat water for later use and therefore avoids using electricity after. Compact short-term storages can also be used on a building level insuring increased end user flexibility. On the other hand, seasonal storages are also being tested currently and although the costs and heat losses are still too big for a larger scale use, it is expected to be an important technology in the future [19]. One of the applications of seasonal storage includes storage for heat produced by solar thermal DH plant. It stores the heat produced in summer when there is lower heat demand and increased insolation for use in winter when the heat demand is at its maximum and insolation is significantly decreased. Some of the technologies for seasonal thermal storage include aquifers, boreholes, caverns, pits etc.

It should be mentioned that using DH systems for utilizing excess electricity production is not a new concept. It has already been used during second half of 20th century in Northern European countries when sudden increase in electricity production capacities occurred.

Heat pumps and electric boilers where used then to consume the excess electricity produced by new nuclear power plants and hydropower plants, while in the future they will be used for consuming excess electricity from renewable energy sources [23].

Excess heat in the future systems will come from new energy conversion technologies such as biomass gasification plants and electrolyzes [19]. All of these resources are low temperature resources and therefore the low temperature DH system is needed with average supply temperatures of around 50 ºC and average return temperatures of around 20 ºC [11]. The benefits of such a system are many with the most important being higher coefficients of performance in heat pumps, higher conversion efficiencies in central solar collector fields, higher power-to-heat ratios in steam CHP plants, higher heat recovery from flue gas condensation and lower distribution losses in the system [22].

One of the biggest barriers for low temperature DH systems though is dissemination of legionella bacteria in DHW storage tanks as mentioned earlier. There are multiple solutions to this problem and some of them are presented as follows. One possible solution is the use of substations without DHW storage tank (direct DHW preparation) and with the minimum volume of water in pipes between heat exchanger and tap [24].

Since direct DHW preparation requires high heating power, this solution would demand a way to reduce resulting high peak loads e.g. installing storage tanks on the network side. On the other hand, if the storage tank is still in use, the system with microboosters (e.g. heat pumps, solar energy, electric heaters etc.) in substations can be used to heat DHW above the needed temperature [12]. Some other technologies include ultraviolet sterilization and reverse osmosis but these technologies are expensive and cannot be used in a large scale DH system [19].

The other important barrier for low temperature DH systems is buildings and their ability to provide thermal comfort in the low temperature system. Since the majority of building stock in Europe is built in the previous century or even before, the thermal insulation of those buildings is minor if even existent. In order to provide those buildings with low temperature heat and ensure thermal comfort of the user, refurbishments with energy saving measures have to be made.

Integration of high temperature heating systems (e.g. biomass CHP or industrial waste heat) with low temperature heating systems can be done by means of cascade energy usage. That way the low temperature buildings can be supplied by the return line of high temperature system and the low temperature heat sources can supply heat into the return line of the system [25]. Although there are currently only a few pilot projects for cascade energy usage, the technology for its implementation is already fully developed and it is expected to be more widespread in the future if proper planning is used. The principle of the cascade energy usage is shown in Figure 4.

Another part of the system, which is affected by distribution temperatures, is the piping system. Low temperatures allow different piping materials (e.g. flexible plastic piping), which result in more cost effective installation techniques and the lower costs of pipes. Installation of new pipes or maintenance of old ones often presents inconvenience for people living in the affected area. New pipes should be installed using the trenchless technology or narrow trenches, that way enabling non-invasive construction and maintenance of DH systems [19].

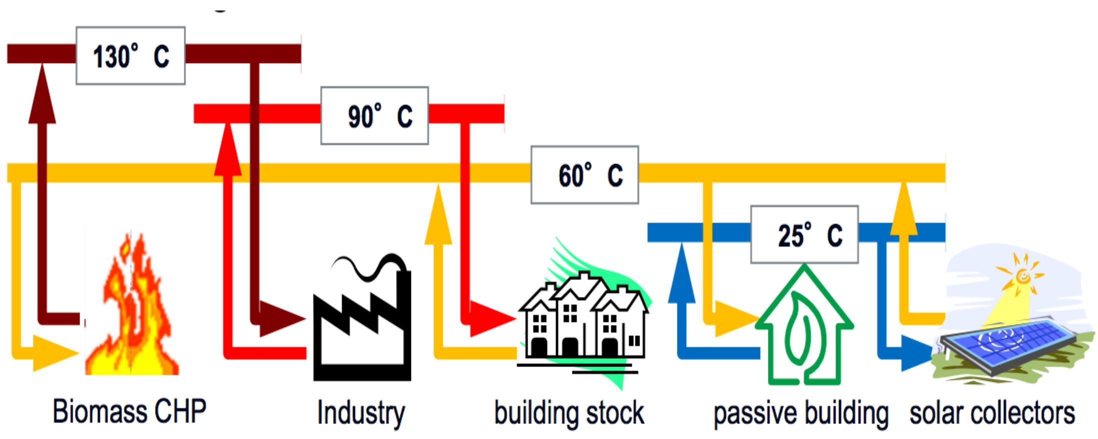

Figure 4. Cascade energy usage [22]

In the future, the amount of heat from CHP will decrease continuously, but it does not mean that DH will decrease. On contrary, DH will be extremely important but the supply of heat to the DH network will be much more diversified and DH systems will be integrated with other sectors into smart energy systems. Since planning and operation of CHP units is currently greatly influenced by the heat supplying cost and heat demands, this will make a considerable problem during implementation of smart energy systems due to its focus on overall system feasibility and not only on heat supply feasibility. Therefore, heat supply planning should not be done independently from energy system planning [6].

The knowledge of future demand levels for various customer groups, e.g. industrial, agriculture, residential and service sectors, as well as the interaction between those sectors in terms of demand levels is essential for implementing smart thermal systems.

Collecting and using this data efficiently is vital for this aspect. Heat meters that are more intelligent as well as making active gathering of data a routine will make having valuable information about the customer demands and flaws in customer thermal systems possible. On the one hand, this information will help the thermal network operator to manage the grid in the most efficient way. On the other hand, consumers will be better informed about their consumption and about the possibilities to decrease their energy bills.

Although smart meter technology is currently not represented in DH systems as stated in previous subchapter, the dissemination of distributed heat generation systems in DH network is expected to stimulate the use of smart meters in future DH systems. Since smart electricity meters are already in use, it is also expected for smart heat meters to become market-ready products soon.

Smart heat meters will help faster and less expensive detection of different faults in DH system. In order to identify and solve faults in DH system and thereby increase system efficiency, continuous commissioning of substations and secondary systems is necessary. Fault detection can then go from being reactive to becoming proactive [26].

Smart heat meters as a part of demand side management (DSM) are showing particularly great potential for implementation at large-scale customers (e.g. swimming pools, industrial customers, large office buildings, supermarkets etc.) where they are expected to be very cost effective [19].

One of the main reasons for using DSM is reducing daily peak loads in the DH network, which are currently covered mainly by fossil fuel boilers, which lower economic and environmental advantages of DH system. Overall implementation of DSM should incorporate planning and monitoring of consumers energy use, this way ensuring optimal operation of the buildings and DH system [27]. DSM can use weather forecasts to determine needed heat for individual rooms in a building. By using thermal capacity of buildings (discharging before excess solar gain occurs) it increases efficiency of DH system and can also help in reducing peak load during the day with peak shaving control system [11].

EU policy that underpins technologies mentioned in this subchapter is Energy and Climate Policy as well as Research and Innovation Policy. They recognize advanced energy technologies as crucial factors when fighting against climate change and improving energy supply security. Acting as a pillar to the above-mentioned policies is Strategic Energy Technology Plan, which aims to accelerate the development and deployment of low-carbon technologies. The SET-Plan promotes research and innovation efforts across Europe by supporting technologies with the greatest impact on the EU's transformation to a low-carbon energy system. It promotes cooperation amongst EU countries, companies, research institutions, and the EU itself [28].

Summary of the characteristics of smart DH systems as well as its components is given in Table 1, in order to give a clear overview of Chapter 2.

Table 1. Main characteristics/components of smart DH system

Heat production system	Using RES for production of heat which stimulates distributed supply
	Utilising low-temperature waste heat from industries, commercial buildings and consumers
	Use of low-temperature system with supply/return temperatures around 50/20 ºC
	Use of large-scale heat pumps and thermal storage providing balancing for the electricity network
	Use of both short-term and seasonal thermal storage
Distribution system	Use of cascade systems in order to integrate high-temperature DH systems with low-temperature DH systems
	New piping materials (e.g. flexible plastic piping) which result in more cost effective installation techniques and the lower costs of pipes
	Using non-invasive construction and maintenance technologies e.g. trenchless technology or narrow trenches
Communication with end-user	Collecting and efficient use of data by the means of smart heat meters
	Proactive fault detection
	Use of demand side management in order to reduce daily peak loads in DH network

3. IMPORTANT ASPECTS FOR REPLICATION

In order to replicate measures of transforming the heating system of one city (or the part of the city) to the smart DH system as a part of the smart energy system, different aspects have to be considered. Aspects that are considered the most important are:

- geographical aspects
- financial aspects
- technical aspects
- ownership aspects

Each of these aspects have to be thoroughly examined before the replication process begins and it has to be accepted that all of this aspects are interconnected. In the following pages, the analysis of the listed aspects will be made as well as the brief description of limitations for implementation of smart DH system.

3.1. Geographical aspect

One of the most important aspects in this analysis is geographical aspect. The geographical position of different cities in Europe differs significantly. Different latitudes, longitudes, altitudes and terrains of cities result in different climates, different RES potentials, different heat demands , different building stock, etc.

For the purpose of analysis, geographical aspect will be divided into three parts: climate aspect, building stock and renewable energy sources potential.

3.1.1. Climate aspect

3.1.1.1. Climates of Europe

Europe has a lot of different climates but the most common are: warm humid continental climate which is typified by large seasonal temperature differences (warm to hot summers and cold winters); oceanic climate which is typified by relatively narrow seasonal temperature range with warm (but not hot) summers and cool (but not cold) winters; hot-summer Mediterranean climate with hot and dry summers and cool and wet winters; and humid subtropical climate with hot, humid summers and mild to cool winters [29].

The far north of Europe and some mountain parts of central Europe have a subarctic climate with long, very cold winters and short, cool to mild summers.

The variety of climates results in different mean temperatures for different parts of Europe as shown for winter months in Figure 5 with higher mean temperatures occurring in southern Europe and lower mean temperatures in northern Europe as expected. This in turn results in different heat demands in cities which has a big impact in making a decision whether to implement a smart DH system in the city. The simple rule is: the colder the climate of the city and the higher the desired indoor temperature, the greater is the heat demand for space heating.

It has to be noted that the heat demand is both the result of outside temperatures as well as of the technical parameters of buildings (i.e. amount of isolation, quality of doors and windows etc. which define the heat losses of buildings) but in this analysis the heat demand will be taken into account under climate aspects since the influence of outside temperature is bigger than of technical parameters of buildings. It was shown in [20] that interdependance between average heat demand and outside temperatures is basically linear. Daily values differ slightly due to solar gains, wind chill and transient heat demand.

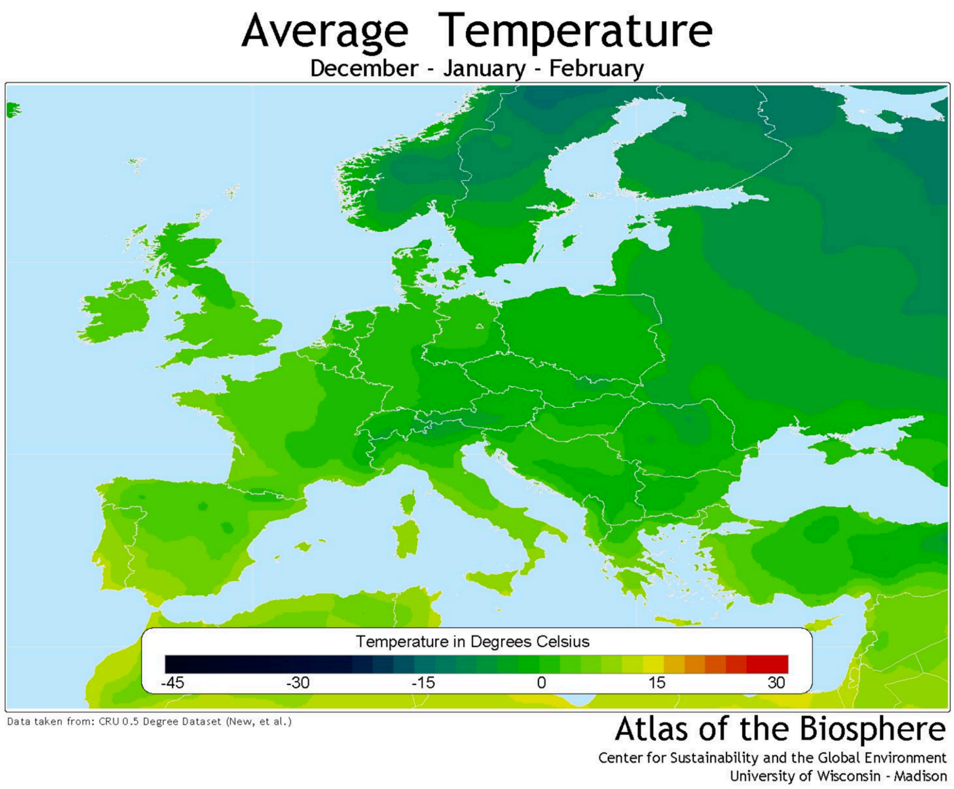

Figure 5. Average temperature in Europe for winter months [30]

3.1.1.2. Heat demand

Heat demands can basically be divided into three types: high temperature heat demand, medium temperature heat demand and low temperature heat demand. Different temperature levels of types of heat demands are reported in literature. For example in [31], high temperature heat demand is defined for temperatures above 400 ºC, medium temperature heat demand is defined for temperatures between 100 ºC and 400 ºC and low temperature heat demand is defined for temperatures below 100 ºC.

While high temperature and medium temperature heat demands mostly occur in industry (e.g. heat used for processes of drying, evaporation, manufacturing of metals, ceramics, glass etc.), low temperature heat demands mainly occur in space heating with some heat also being used for low temperature industry needs (e.g. washing, rinsing and food preparation). District heating systems are used for covering low temperature heat demands (although it can be used for covering some medium temperature heat demands as well, with the use of temperature boosting at the end-user via e.g. heat pumps) hence heat demand is taken into account under climate aspects.

In order to implement a smart DH system in a smart city (whether building a completely new system in a city that did not have a DH system or improving and expanding the existing network to transform it into smart DH system), mapping of the heat demand has to be done since feasibility of implementing a smart DH system is dictated by the amount of heat that can be sold over certain area. For that purpose, heat demand density is used which represents the total heat demand of a land area, city or settlement. Basically, if heat demand density of an area is high than it is feasible to use district heating system in that area. It has to be mentioned that heat demand density is not a static value in time but it changes due to different aspects e.g. global warming or energy efficiency measures in buildings [32].

Mapping should be done by the means of heat atlas which provides a GIS based analysis. If a heat atlas already exists for the area in which the implementation of smart DH systems is to be done, than the existing heat atlas should be used. Otherwise, a new heat atlas should be made by the experts. There are a number of projects (e.g. Heat Roadmap Europe [33], Stratego [34], etc.) which provide heat atlases on a 1 km^2 scale covering large parts of Europe. Examples of heat atlases are shown in Figure 6 for a larger scale (EU-27) and Figure 7 for a smaller scale (city in Croatia).

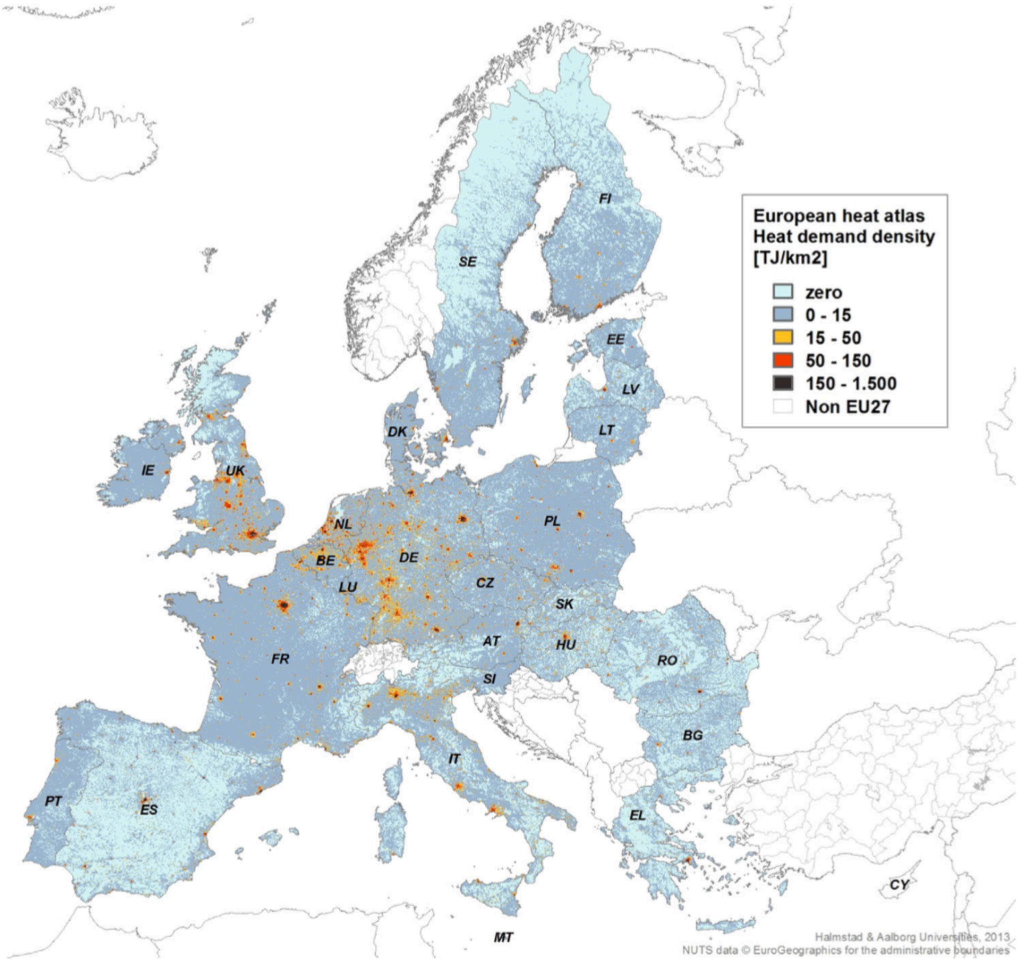

Figure 6. Heat atlas for EU-27 showing heat demand densities [33]

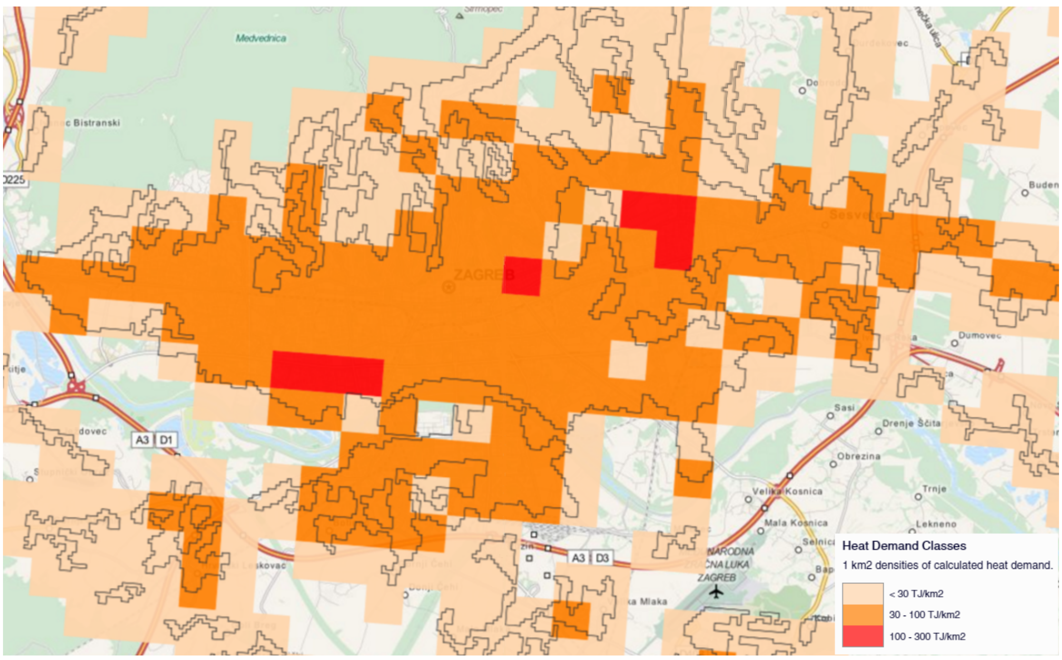

Figure 7. Heat atlas for a city with the resolution of 1 km^2 [34]

3.1.2. Building stock

Buildings represent an important aspect in Europe, not only from the smart DH system point of view, but in general, since they have emotional and architectural value to the society. Although new buildings can be constructed with high performance levels, older buildings on the other hand have significantly low energy performance and they make the most of current building stock in Europe as can be seen in Figure 8. It can be noted that the age of the buildings remains roughly the same regardless of geographical position of buildings.

Because of their age (old buildings consume more due to their low energy performance), buildings make one of the most significant CO_2 emission sources in Europe, but it also makes them one of the most significant aspects in sustainable future due to their potential to deliver high energy and CO_2 savings [35].

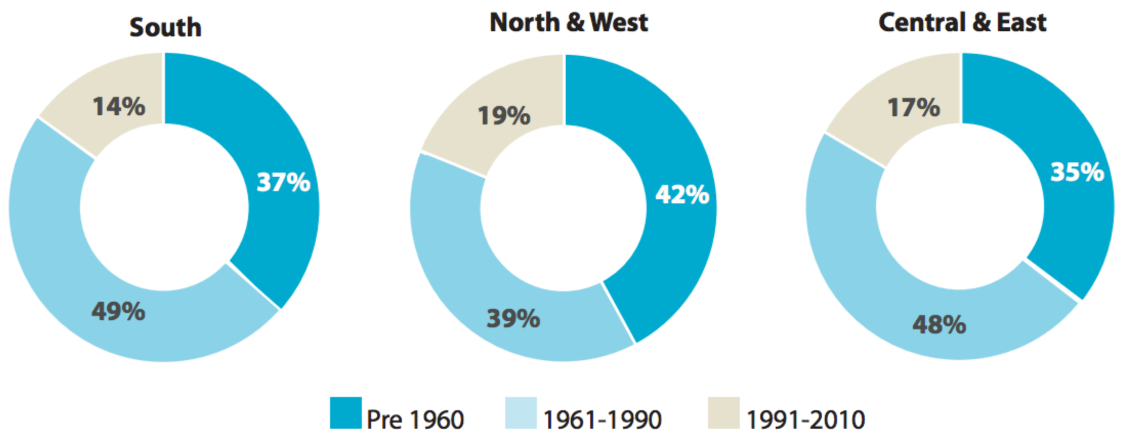

Figure 8. Age of building stock in different geographical parts of Europe [35]

Different parts of Europe incorporate different types of buildings. Generally, two main types of buildings that can be defined are residential and non-residential buildings with various subtypes of each type in every country. Residential buildings make the majority (around 75 %) of EU building stock. Depending on the position of the city in Europe, different subtypes of buildings can be defined with different levels of energy saving measures incorporated.

Countries in southern Europe, although having lower energy needs because of the mild winters, incorporate higher levels of energy consumption due to lower thermal insulation levels of buildings. In northern European countries on the other hand, thermal insulation regulations exist for a long time, therefore those countries achieve higher levels of thermal insulation in buildings and lower energy consumption [35].

3.1.3. Renewable energy sources potential

Since smart energy system represents a 100 % renewable energy system and a smart DH system is a part of smart energy system, it is essential to map the local potentials of RES. The most important sources that can be used for a smart DH system are wind, solar irradiation, geothermal resources and biomass. Different cities have different potentials for utilization of those resources with some cities being able to implement all of this resources into smart DH system and some cities having lower potentials for RES utilization.

3.1.3.1. Wind

The kinetical energy of wind is used for producing electricity by the means of wind turbines. This electricity can be used in a smart DH system for powering heat pumps or electric boilers (i.e. thermal storage). That way the smart electricity system gets integrated with the smart DH system and the value of wind power is increased.

Meteorological data should be used to map the wind speed of an area. Wind speed data is usually collected for the heights of 80 m since it is an average height of a wind turbine hub. Coastal areas have much better potentials for utilization of wind energy as can be seen in Figure 9. Unrestricted technical potential for offshore wind energy up to 2030 is highest in France (5300 TWh), Sweden (5000 TWh), Great Britain (4600 TWh) and Finland (4500 TWh) [36].

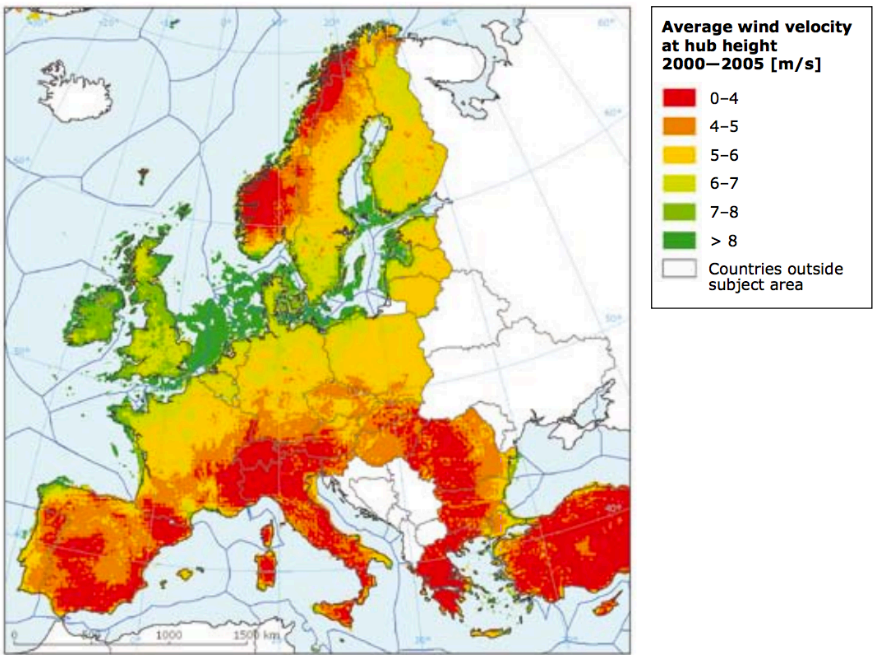

Figure 9. Average wind speeds for Europe for time span of 2000-2005 [36]

The inland parts for the most of Europe are not suitable for utilization of wind power, although some inland parts (e.g. Denmark and Great Britain) have high annual mean speeds of wind which can be utilized for electricity production. This can be seen in the unrestricted technical potential for onshore wind energy up to 2030 for central European countries like Switzerland (100 TWh), Austria (500 TWh) and Hungary (600 TWh) [36].Wind speeds are traditionally highest at sea as can be seen in Figure 9 so the coastal cities can utilize wind power from both onshore and offshore wind turbines. For example, unrestricted technical potential for offshore wind energy up to 2030 is highest for Great Britain (4900 TWh), Denmark (2700 TWh) and Netherlands (2300 TWh). Since 40,8 % of people in EU lived in coastal areas in 2011 [3], it can be concluded that wind power represents an extremely important technology already today, as well as it will in the future smart energy systems.

3.1.3.2. Solar irradiation

Solar irradiation as a renewable energy source can be utilized in two ways: for electricity production or for heat production. The technology being used for heat production is called solar thermal. Solar thermal represents a low-temperature heat source which can be utilized in low-temperature smart DH systems. When being used in a smart DH system, this technology also requires thermal storage units because when the production of heat by solar thermal is high, the heat demand is low and the heat has to be stored for later use. Seasonal storage should be used to utilize the heat produced during summer (when the heat demand is low) in winter months (when the heat demand is high).

Meteorological data for solar irradiation are accessible and can be used to determine the potential for utilization of solar thermal at the given area. As expected, solar irradiation is highest at the southern parts of Europe while it is lowest at northern parts of Europe as seen in Figure 10. For example, annual global horizontal irradiation for a town in southern Europe (Malaga) is 1870 kWh/m2, for a town in central Europe (Munich) 1160 kWh/m^2 and for a town in northern Europe (Helsinki) 935 kWh/m^2. Nevertheless, there are examples of using solar thermal for DH systems at the northern parts of Europe with inclusion of seasonal thermal storage with Denmark being the worlds leader with around 576 000 m^2 of solar collectors currently providing 403 MW of thermal power to 61 DH system [37].

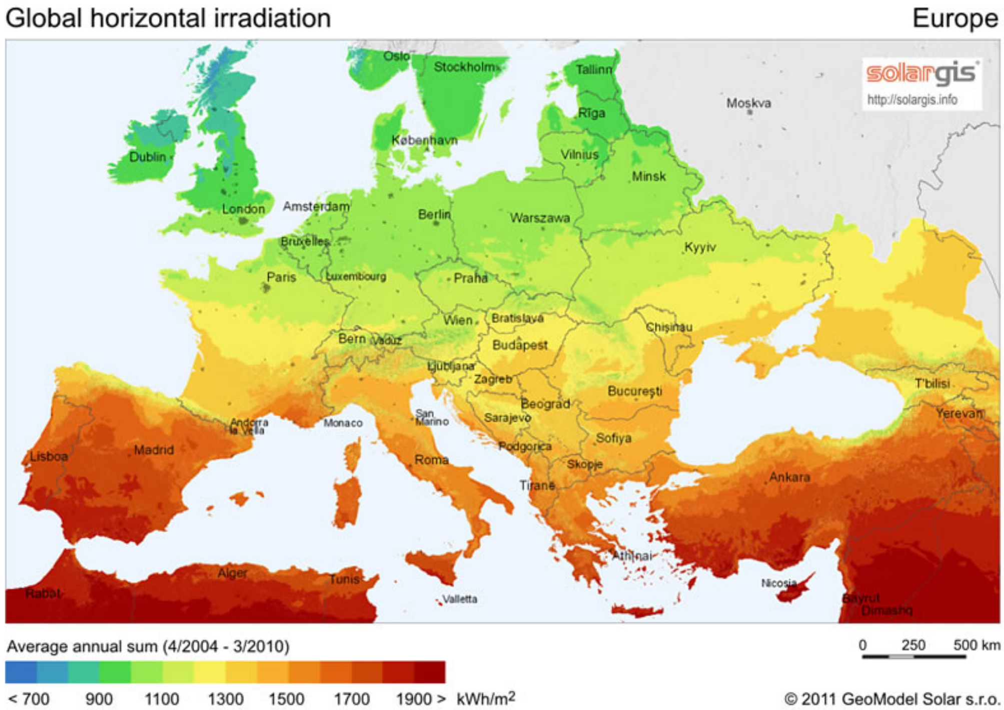

Figure 10. Annual global horizontal irradiation for Europe [38]

3.1.3.3. Geothermal energy

Geothermal energy is a low temperature energy source for DH which has a big potential in all European countries since geothermal energy in one form or another is present everywhere in the world. It is already being used in a number of European countries and many other countries are planning on implementing such systems so it is expected that nearly all European countries have geothermal DH systems by 2020. Depending on the temperature of the geothermal heat, it can be used as a stand-alone system or as a hybrid system with some other technologies (e.g. heat pumps) for covering peak loads. Using a DH system for exploiting geothermal heat is much more cost effective than using an individual system because of DH system's aggregating capabilities (i.e. making a geothermal well costs the same if it is for one house or for a district heating system) [39].

In order to determine the potential for using geothermal heat for smart DH systems in a given city it is necessary to map the potential by analysing available geological data and the heat demand of an area.

Maps have already been developed for some countries in Europe (e.g. project geoDH) [40]. For example, in Denmark, geothermal DH could serve 75 % of the population (it could serve the whole Copenhagen area), in Bulgaria 50 %, in France 37 %, in Germany around 50 % etc [40].

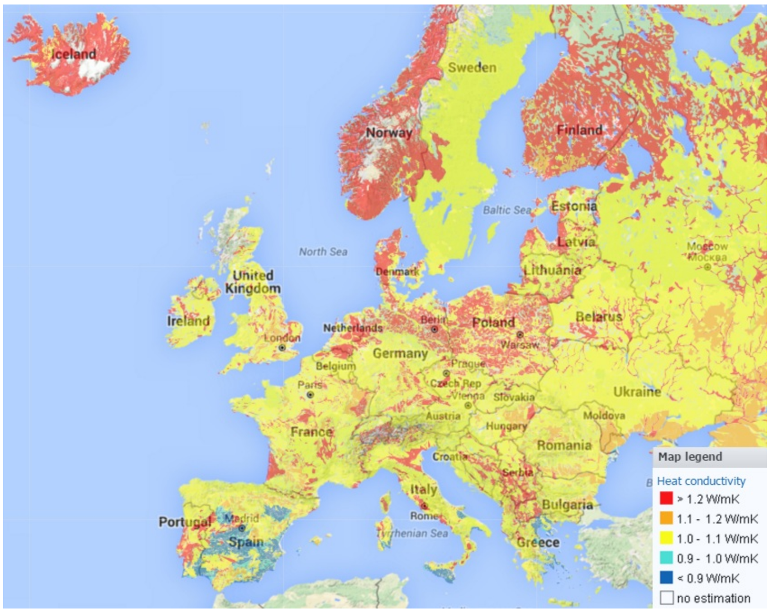

Figure 11. Map of geothermal potentials in Europe [40]

3.1.3.4. Biomass

Currently, biomass is the most used renewable energy source for DH systems. It is incinerated in a solid or gaseous form, mostly in CHP units for production of electricity and heat. Biomass is also used for heat-only boilers in DH systems.

Biomass includes residual sources such as wood, crops, straws, biogas etc. Although most experts classify biomass as a renewable energy source, it has to be noted that biomass influences GHG emissions depending on the nature of the biomass resource, the way it is utilised and some other important aspects e.g. whether new trees are planted or not. Therefore it has to be assured that biomass is used in a sustainable way.

In the smart DH systems, it's primary use will also be in CHP units, although with smaller share of solid biomass and a bigger share of biogas or syngas produced by biomass gasification process. Before the implementation of a smart DH system, the local potentials of a city for different sources of biomass should be mapped.

After that an analysis should be done to research the actions for possible increase in the potential, such as a shift in forest management practices and cereal cultivars, enacting dietary changes etc. [9]

It is important to notice that biomass potentials depend on different aspects in future so careful planning is needed. For example, different scenarios have been proposed in [41] for different sources of biomass. As an example, the map is shown for common sludge potential in Figure 12. For example, potential energy from common sludge in 2020 in Denmark equals to 286 ktoe, in Germany 280 ktoe, in Bulgaria 75 ktoe and in Hungary 111 ktoe [41].

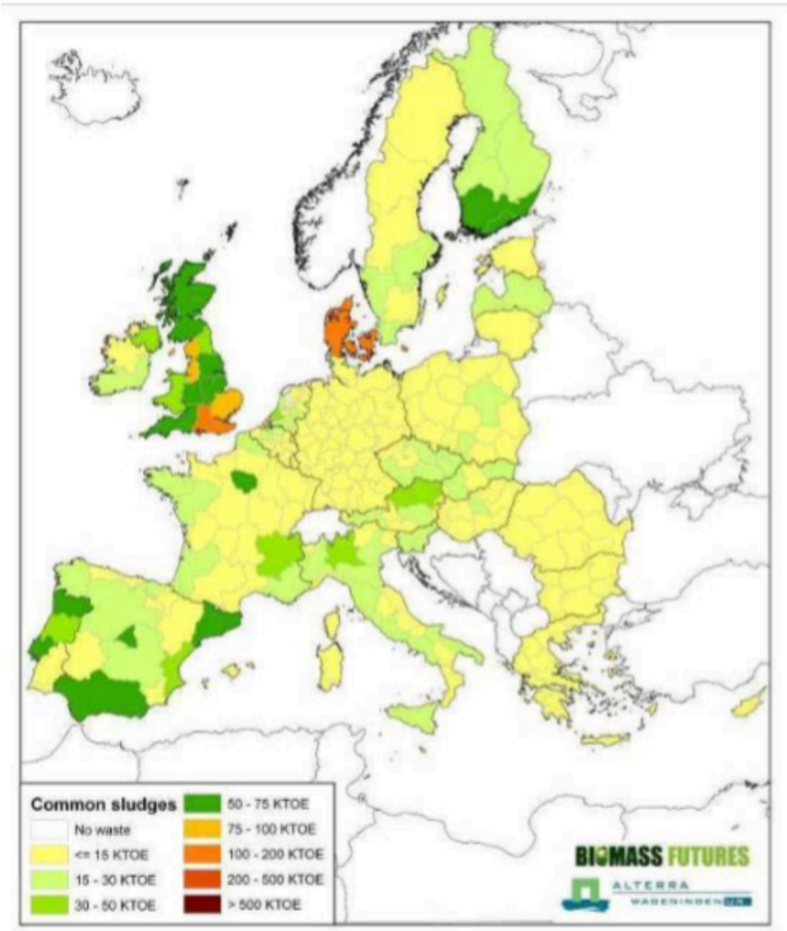

Figure 12. Potential energy from common sludge [41]

3.2. Technical aspects

Technical aspects of current DH system in a city, along with local excess heat sources and storage possibilities also have to be elaborated if a smart DH system is to be implemented.

3.2.1. The state of existing heating system

Different cities in Europe have different shares of DH covering their heat demand. There is a number of cities which have no DH system installed at all and also a lot of cities which have a high share of DH. Cities with already existing DH systems should analyse the state of their systems in order to determine which parts of the system need to be transformed for the implementation of a smart DH network.

Some systems in Europe incorporate outdated technologies which is also due to the age of those systems. Such systems can be found in parts of eastern, central and south-eastern Europe which still use vapour in some parts as a heat carrier in the network and therefore distribution temperatures are rather high. Those networks also have old piping systems which cause major heat losses along with water losses during the year. It is obvious that those systems would have to be completely replaced by new system instead of just upgrading certain parts.

On the other hand, cities and municipalities in northern and western Europe invest more in newer technologies considering DH system. Those networks include better piping systems with minimised water and heat losses, they have lower distribution temperatures (with temperatures significantly below 100 ºC) and basically they are completely part of the 3rd generation DH systems [42]. Some of those systems already incorporate some features of smart DH systems and therefore it would be technically easier to transform such systems into a smart DH system.

When it comes to heat sources being used for DH system, a number of cities in Europe still have coal or oil driven DH systems which present a significant source of GHG emissions. Natural gas is also a widely used heat source. Some cities have already incorporated RES into their DH systems and in those cities it would be much easier to implement smart DH network.

Examples of such cities include Sønderborg with 50 % share of RES in a DH system [43], Copenhagen with also 50 % share of RES [6] and Tartu with almost 100 % share of RES (only top load is covered by natural gas boilers) [43]. Less advanced systems, on the other hand do not have any renewable energy sources in their fuel mix and therefore the transition to smart DH system will be much more difficult.

3.2.2. Excess heat mapping

One of the important potentials for the DH system now, and in the future is the use of exploitable excess heat as a heat source. This excess heat can come from various facilities such as energy intensive industrial sectors (e.g. chemical and petrochemical, iron and steel, non-ferrous metals, non-metallic minerals, paper, pulp, printing, food and baverage), fuel supply, refineries, supermarkets, etc. Different cities have different amounts of excess heat available and different sources they are available from. There is actually enough waste heat produced in the EU to heat EU's entire building stock there is just not the heating distribution network available to transport it to where it is needed and can be used [31].

In order to determine those potentials for excess heat use in a DH system in a city, first it is necessary to geographicaly define the locations of such facilities by researching databases of current and future, planned facilities in the area. After that, the second step is to quantify annual excess heat volumes available from certain plant in order to determine the magnitude and extent by which these assets may be utilized to replace current heat supply to meet building heat demands [44]. Some mapping has already been done by the Stratego project on the scale of EU-28 as can be seen in Figure 13.

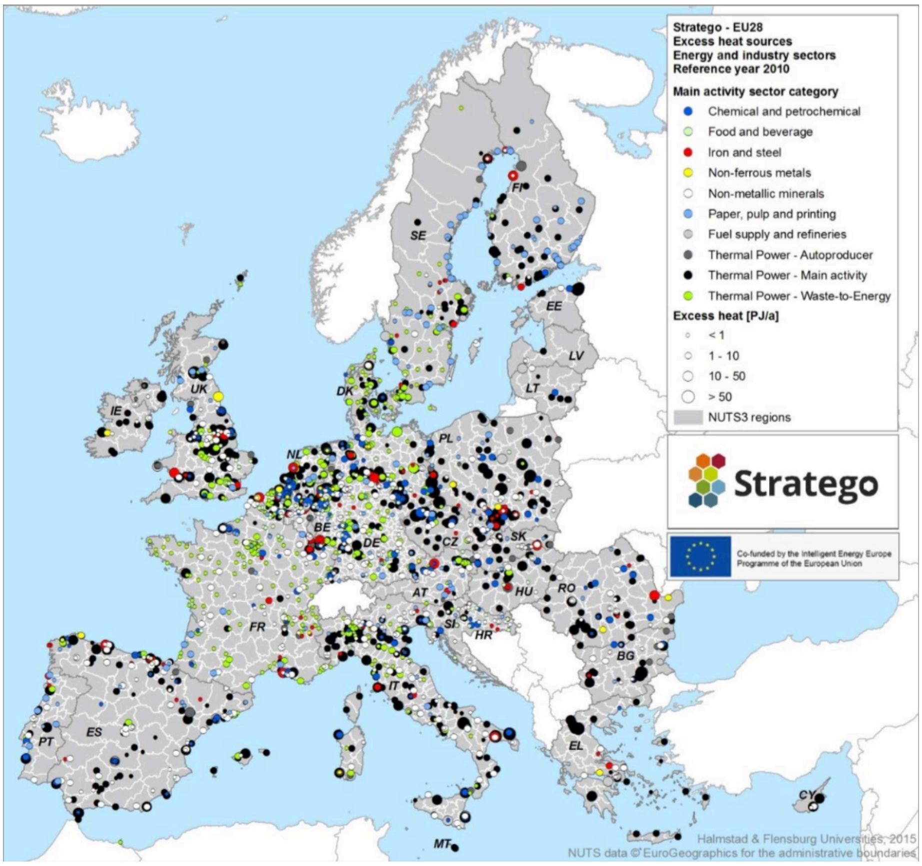

Figure 13. EU-28 excess heat facilities with assessed annual excess heat volumes [44]

It can be concluded that the majority of excess heat facilities that are currently existent are in the large urban areas or close to them and therefore the potentials for the use of excess heat in smart DH systems are significant. Currently, approximately 70 % of all available excess heat originates from thermal power generation, being by far the richest source to exploit in the future smart DH systems.

Relative share of industrial excess heat equals to 26 %, while the relative share of waste-to-energy incineration is 4 %. Germany, Spain, France, Italy, the Netherlands, Poland, and the United Kingdom account for a major share of the total primary energy supply (approximately 72%), which is correspondingly reflected in anticipated excess heat availabilities [44].

3.2.3. Thermal energy storage units

Variations of heat load, whether they are daily or seasonal, give incentives for the use of thermal energy storage in DH systems. Seasonal heat load variations in Europe come from different seasons which result in different outdoor temperatures and therefore different heat demands for space heating. Daily heat load variations, on the other hand come from social use patterns for DHW preparation and different working patterns of the building heating systems.

Thermal energy storage units are then used to move the heat generation to times when the load is lower and therefore the cost of heat generation is lower. Also they can be used to utilise excess electricity from RES in order to produce heat that can later be used and therefore participate in balancing of electricity sector. An example of seasonal and daily heat load variations for DH systems in Sweden with an annual heat demand of 4400 TJ is shown in Figure 14.

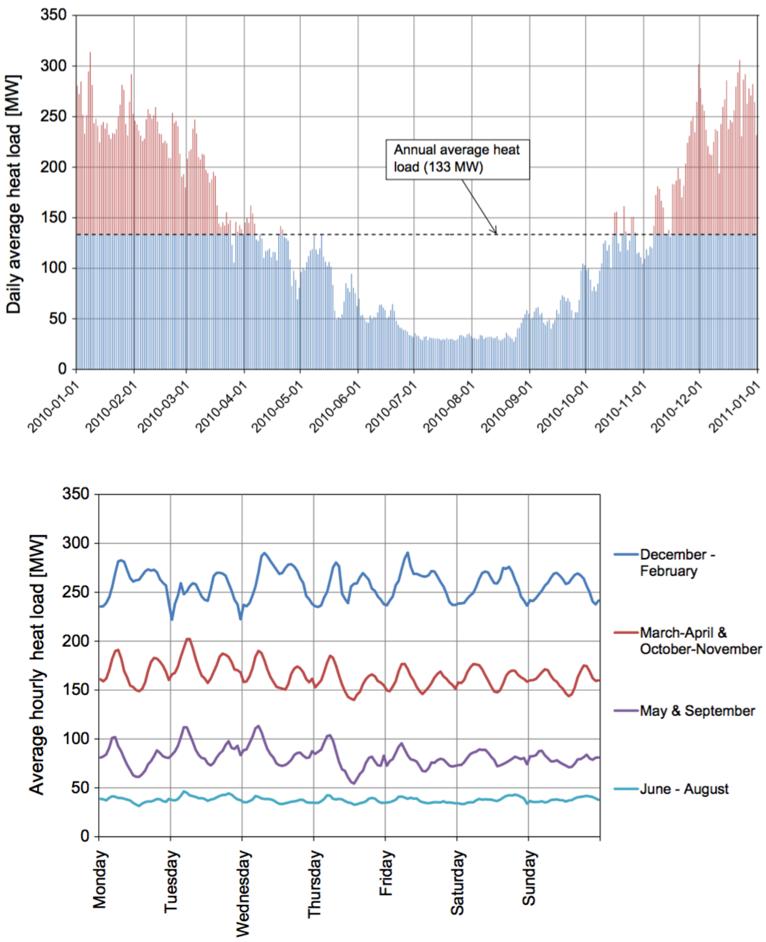

Figure 14. Seasonal (up) and daily (down) heat load variations for Swedish DH systems [45]

In terms of profitability, the thermal energy storage unit solving many daily load variations is expected to reach acceptable profitability much easier than the thermal storage unit solving seasonal load variations since it provides much more cash flows during the year [46].

Thermal energy storage units for daily use are most often placed at the site of the heat generation plant and therefore they do not represent a problem when it comes to space usage. They should be considered for implementation when planning the smart DH system since they provide significant savings mainly because of fuel savings, optimization of electricity production in CHP plants and reduction of peak boilers usage as already mentioned. An example of such a system is a new, 750 MWh heat accumulator in Zagreb DH [42].

Seasonal thermal storage units (they are also called inter-seasonal thermal storage units) can represent a problem when it comes to space usage due to technologies that are used for those units such as e.g. aquifers, pits, boreholes underground tanks etc. Those storage units require large volumes of mostly underground space with values usually over 100 000 m^3 [20]. One example of seasonal thermal storage includes Sunstore 4 project in Marstal DH system which added 15 000 m^2 of solar thermal, connected to a pit thermal storage of 75 000 m^3 to an already existing system. The price for heat storage was 39 €/m^3 including in-and outlet, transmission pipes, pumps, geo-technical support etc. Denmark is the worlds leader when it comes to solar DH systems with a large number of systems being continuosly implemented all over Denmark [47]. Another example is a seasonal thermal storage system at Friedrichshafen in Germany, a 12 000 m^3 storage with a capacity of approximately 0,84 GWh [48].

It is assumed that seasonal thermal storage units will be used primarily alongside solar thermal DH plants to store the heat generated during summer for use in winter. Since the use of solar thermal in DH systems also requires a lot of free space, which is not easy to find in a city, detailed planning will be crucial if those systems are going to be used as a part of smart DH system.

When it comes to costs of thermal storage systems, they are strongly related to storage size. Small tank storage systems of 300 m^3 of water cost about 470 €/m^3 compared to a cost of 120 €/m^3 for a 12 000 m^3 store. For seasonal thermal storage systems (aquifers, boreholes and pits), prices are much lower. For example, 5000 m^3 aquifer storage costs around 40 €/m^3, while a 75 000 m^3 pit store costs around 30 €/m^3 [48].

3.3. Financial aspects

Finances always make an extremely important aspect regardless of the subject being elaborated. When it comes to replicating smart DH systems in cities, two financial aspects stand out: feasibility of the implementation of smart DH system and funding of the implementation of smart DH system. Both aspects should be examined before implementing smart DH system in a city.

3.3.1. Feasibility

In order to determine feasibility of implementing a smart DH system in a city, it is important to define relevant costs. When it comes to smart DH system, the feasibility of the system consists of heat generation cost difference between DH system and an alternative system and the heat distribution cost. But since it is necessary to implement heat savings in buildings for proper operation of the smart DH system, it is also necessary to determine feasibility of implementing heat savings in buildings.

It is important to note that if a DH system is already existent in the city it is necessary to determine whether the DH system has been completely payed off before the upgrading of the system. Currently operating DH infrastructures (including the energy generation facilities) are planned, financed and operated in given contractual conditions, which cannot easily be amended to facilitate the further development of innovative smart thermal networks.

3.3.1.1. Future competitiveness of smart DH systems

If a city plans to implement a smart DH system, it is necessary to determine the costs of such a system, whether the current DH system is being converted to smart DH system or a completely new smart DH system is being built. Total heat costs of a smart DH system consist of heat generation costs and heat distribution costs while the heat costs of individual systems consist only of heat generation costs as can be seen in Figure 15. Therefore, the sum of heat generation costs and heat distribution costs for a smart DH system should be lower than for alternative systems.

Heat generation costs consist of different costs, e.g. fuel costs, investment cost (e.g. building a new plant, integration of processes, building a thermal storage unit etc.), electricity costs for auxiliary needs, external costs etc. [49]

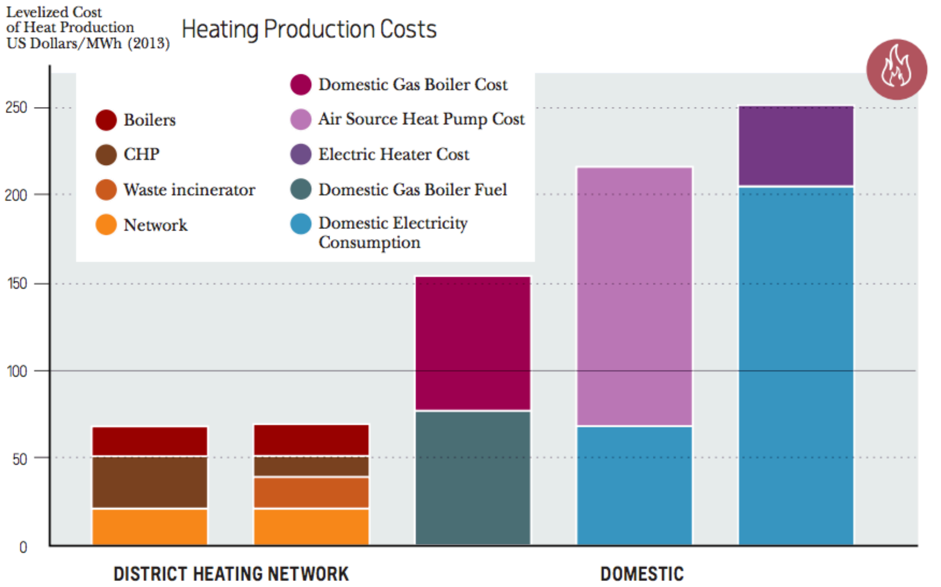

Figure 15. An example of levelized costs of district heating compared to individual production (prices will vary significantly by location and project) [16]

When it comes to distribution costs of a smart DH system, the network construction cost has the biggest share and it is directly influenced by the linear heat density which is the quota of heat annually sold and the total trench length of the district heating pipe system. So, determining the linear heat density is the most important part in calculating distribution costs of a smart DH system. Most parts of European cities are dense enough for the linear heat densities to be large and therefore for the distribution costs to be rather low [32]. It has to be noted that prices will vary significantly by location and project. Distribution costs often amount for up to half of the overall costs of DH systems. An example of network costs and connection costs for different linear heat densities is shown in Figure 16.

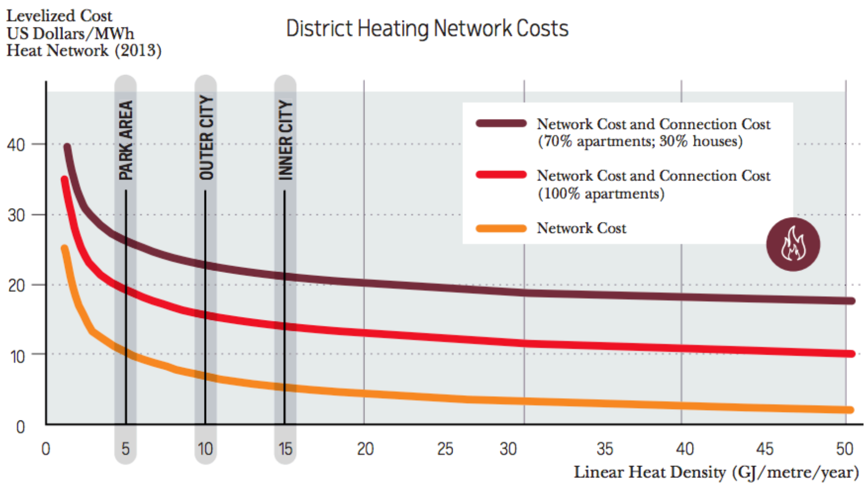

Figure 16. An example of network costs for DH systems [16]

For linear heat densities of 15 GJ/m/a or more, which corresponds to an inner city area, distribution costs (with connection to only apartments) decrease to around 10 $/MWh and remain the same for higher linear heat densities [16].

Sum of capital costs for a smart DH system, which is the most important part of costs, equals to about 1,5 - 2,5 € million/MW$_{th}$ [19]. In order to determine costs for heat production from different plants in a smart DH system, variation of prices has to be taken into account again as mentioned earlier. An example of plant costs and operational costs for DH system is shown in Figure 17.

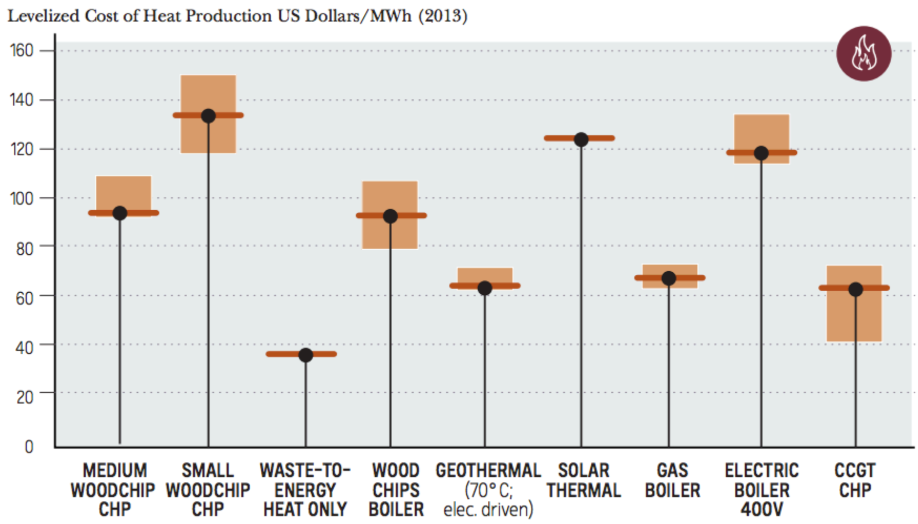

Figure 17. Centralized plant costs and operational costs for district heating systems [16]

Costs shown in Figure 17 are calculated for specific conditions (e.g. CHP load factor is 40 %, waste incinerator load factor is 80 %, gas/electric boiler load factor is 10 %, discount rate is 10 %, etc.). It can be seen that the lowest costs are for waste-to-energy plant with around 40 $/MWh, while the highest costs are for small woodchip CHP, solar thermal and electric boliers, all of them having costs above 120 $/MWh [16].

3.3.1.2. Feasibility of implementing heat savings in buildings

In order to implement smart DH system, buildings will have to be refurbished, with energy saving measures like improving insulation of walls, changing windows and doors, using heat recovery in buildings etc. Important aspect is feasibility of heat savings in the smart city buildings. It depends on the present state of the building which is tightly connected to the age of the buildings.

In new buildings, passive house or low energy concepts should be considered which have a very small heat demand, but in some older existing buildings it is actually assumed that the costs of heat savings per energy unit will be higher than the cost of supplying the remaining heat demand at some point

In most existing buildings though, large amounts of heat savings are expected to be feasible. It is important to notice that not all buildings can be renovated due to different reasons e.g. building protection, historical reasons, cultural reasons, etc. So the first step in analysing heat saving potentials is defining which buildings can be refurbished.

It can be argued that there are two types of costs for implementation of heat savings: direct costs and marginal costs. So if the only purpose of energy renovation of buildings is implementation of heat savings, this is called the direct cost and the chances are smaller for it to be feasible. On the other hand, if the building is being renovated anyway, the costs are called marginal costs and than it is much more likely for the refurbishment to be feasible. Marginal costs correspond to about half the direct costs. Therefore, for individual buildings it is recommendable to implement heat savings when the building is being renovated anyway or when the new building is being constructed [6]. Concerning the prices for renovation of buildings, practice shows that the average price of renovating apartment buildings is 150 €/m^2 but since the renovations needed for implementation of smart energy systems follows higher requirements and includes smart ICT solutions, the price can be estimated at 220 €/m^2 [43].

3.3.2. Funding

Transforming a heating system of a city into a smart DH system requires significant investments in the DH system itself and also in heat savings that have to be done in the buildings. Considerable investments are not the only problem, since a number of cities lack the means and the credit rating to find cheap sources of funding. Therefore it is crucial to deploy all possible financial tools to make a transition to smart DH systems possible and affordable.

Necessity of using EU funding instruments is obvious and local authorities should make a plan on how to take full advantage of all EU funding sources with the support of European Investment Bank (EIB) and other public and private financial institutions. Examples of some European funds that can be used for smart DH implementation are European Regional and Development Fund and Cohesion Fund, which both give grants and indirect funding depending on the project.

Also, SmartEnCity project, for example, will receive EU funds from Horizon2020 which is an EU funding programme for research and innovation running from 2014 to 2020 with a €80 billion budget [43]. City of Vitoria-Gasteiz will receive 1 500 000 € for implementation of smart DH which is 26 % of the whole costs. 54 % of costs will be covered by public bodies (Basque Government and the city of Vitoria-Gasteiz) and 20 % by industrial partners. For the city of Tartu on the other hand, only 2 % of budget (140 000 €) will be covered by Horizon2020, while the rest will be covered by industrial partners. Finally, in the city of Sønderborg, 55 % (1 662 248 €) of the budget will be covered by Horizon2020, while 45 % will be covered by public bodies.

Recommendations for cities on how to develop smart cities with the support of EU funding mechanisms should be researched (e.g. document from European Commission on using EU funding mechanisms for smart cities) [50].

3.4. Ownership aspects

In terms of ownership, there are two main elements that have to be discussed, ownership of the district heating system and ownership of the buildings connected to a district heating system. Both aspects are relevant and have to be elaborated before the replication of a smart DH system to another city.

3.4.1. Ownership of a district heating system

Different DH systems are owned by different stakeholders. DH systems can be in public ownership (state-owned or municipality-owned), private ownership or mixed private and public ownership. Traditionally, in central and eastern Europe DH systems are often incorporated in state-owned national electricity utilities as a department or a branch of the utility and typically not incorporated as economically independent entities. In the western Europe on the other hand, DH utilities are traditionally incorporated as a multi utility systems (e.g. providing distribution and supply of electricity, water, district heating, gas etc.) or they are incorporated as utilities providing DH only.

Recently, the change of ownership in central and eastern European countries from state to private and municipal took place but there is still no definite ownership structure and no conclusions can be made whether private controlled DH companies are more efficient than the public controlled. This is due to the reason that utility performance, price of heat and the quality of services provided depend mostly on site-specific conditions, effectiveness of competition on the local heat market and quality of the utility managers, rather than on the ownership structure itself [51].

Even though it is not clear whether private controlled DH companies are more efficient than the public controlled, a conclusion can be made that it is important for municipalities to have high levels of autonomy and flexibility granted by the government in terms of long-term heat planning since it helps in providing the local community with the most cost-effective heating solutions that are available for that specific community. It also results in expansion and continuous investment in cost-effective DH systems as seen on the case of Denmark [39].

Considering the above mentioned, the best solutions for the smart DH systems of future would probably be the public-private partnerships which can be achieved in different ways (e.g. leasing, concession, operation and management contract, private minority equity partnership etc.) due to their advantages such as the fact that the private sector is best placed to raise capital and deal with risk, while the public sector is best placed to deal with local issues involving a number of different municipal departments.

3.4.2. Ownership of buildings

The ownership of buildings has a large impact on the implementation of smart DH systems in a city since it influences the rate at which the buildings are being refurbished and also the depth of energy saving measures being implemented during refurbishments. It is expected that the public sector takes the lead in implementing deep renovations while for private owners, encouragements, incentives and regulations are needed in order to stimulate reasonable rates and depths of refurbishments.

Ownership of the buildings varies for different European countries but some patterns can be noticed. The majority of European residential buildings are private owned, while the public owned buildings account for 20 % of the residential building stock. The question of tenure is also very important for implementation of refurbishments. At least 50 % of buildings are occupied by owners, with some countries having a higher share and some having a lower share [35].

Non-residential buildings on the other hand are much more diversified in terms of ownership, with values ranging from 10 % to as high as 90 % depending on the country. The extent of public ownership of non-residential buildings suggests that this would be a good target for public policy to begin large-scale renovation to deliver significant reductions in energy use, although the impact would be higher in some countries and lower in another.

3.5. Barriers for replication of smart DH system

When replicating a smart DH system, barriers for smart DH system should be adressed since they will determine which measures and actions are good enough to be implemented. Potential barriers for replication of smart DH system in a city include technical, financial and institutional barriers. For the most systems, technical barriers are not existent since the technology is well known and there are numerous examples across Europe of all sizes. However, barriers will exist in pioniring systems since they will incorporate new technologies which have not been used on a large scale yet.

When it comes to financial barriers, they are reflected in the high costs of initial investments, particularly for heat transport and distribution. Since private sector business demand high rates of return for their investment, they will not invest in such systems unless they will have a major share of the heat market. In successful DH countries the business has been de-risked by for example governments granting monopoly powers to DH companies. So in order to remove financial barrier as well as the institutional barrier, governments should grant similar powers enjoyed by other natural monopolies such as water companies and electric distribution companies. This essentially means monopoly of supply of heat, ability to lay pipes where they are deemed necessary, ground entering, compulsory purchase procedures, widespread road braking and pre-granted planning permissions [52].

4. REPLICATION METHODOLOGY

In this chapter, methodology for replicating a smart DH system as a part of a smart energy system in European cities will be given. Each step of a replication process will be given as a subchapter which will be elaborated. Defining and proposing a methodology for replication will result in a replication flowchart.

The methodology consists of two main parts: preparation process and implementation process. Each of these parts is subdivided into important steps that have to be made in order to successfully implement a smart DH system in a smart city. The methodology was developed in coordination with supervisors and according to [53].

4.1. Important steps of the methodology

In this subchapter, the important steps of the methodology will be elaborated. After the decision has been made to replicate a smart district heating system in a city as a part of a smart energy system, next steps can be identified as follows:

1. building a political support
2. organising first actions and making the first draft of the plan
3. mapping the stakeholders
4. information gathering
5. information analysis
6. best practice analysis
7. proposing actions and measures
8. determining financial framework and proposing implementation plan
9. implementation.

4.1.1. Building a political support

The first step that has to be done in order to implement a smart DH system in a smart city is to build a political support. It has been recognised as a vital step that determines how the project will develop, as already mentioned in the lessons learned from demonstration activities in smart cities.

Parts of government are complex entities i.e. many people which incorporate different laws and responsibilities and have their own problems. It is very important to have a person in the government, a politician who will be responsible for the whole initiative and who will use already existing documents such as Sustainable Energy Action Plans and Energy Visions of the city as the roadmap of the project, i.e. a visionary leader is necessary in order to avoid falling into the same patterns of isolated initiatives and disconnected solutions. This person has to have a sufficient authority in the City Hall, needs to make all the connections inside the government and make sure everyone is on the same page.

After the initiative gets supported by a politician with authority, the next step is to use his authority to gain the support and commitment of all involved areas inside City Hall since this is the key to success. It is necessary to be aligned with the city operations in order not to impact their everyday work and generate the proposed value for all stakeholders [18].

Checking the public opinion and winning public support for the smart DH system initiative may also contribute significantly to specifying with greater precision the proposed objectives and convincing the municipality politicians in their necessity.

4.1.2. Organizing first actions and making the first draft of the plan

After the necessary political support has been gained, the next step should be organising first actions and including them in the first draft of the replication plan. In this step, actions included in preparation process have to be defined (i.e. stakeholders mapping, information gathering, information analysis etc.) and described. Also, the time spans in which the defined actions should be completed have to be determined.

In [19], the proposed time span for preparation process of implementing smart DH system in a smart city is up to two years with the time span for the whole project including the implementation process of up to five years. The time span should be clearly defined for every proposed action in order for stakeholders to have a clear vision of what their tasks are.

Another aspect that should be included in the first draft of the replication plan is the analysis of the existing policies or strategies which concern district heating systems such as documents related to climate change, energy, waste, planning etc. Policies that should be analysed are defined on a city scale, regional scale and national scale. That way, the plan can be underpinned by those policies, making it easier to disseminate it.

Number of policies can help in creating a market for smart DH systems: benchmarking and disclosure requirements of building energy performance; incentives for energy efficient renovation and new construction; measures and standards that provide incentives for the electricity produced in district energy systems (e.g. CHP) with clear, consistent rules for connecting to the grid; priority dispatch; licensing exemptions for small scale generators; and policies that open energy markets to decentralized generators and internalize the public benefits of DH systems (net-metering, heat incentives) [16].

As was already mentioned, city governments represent vital stakeholders in replication of smart DH systems since they have regulatory authority over public procurement and land use and they often partake in ownership of energy utilities. By introduction of the land-use policies, they can set guidelines for urban development plans to consider smart DH systems; service area bylaws that designate areas for smart DH service providers; public and private easements for smart DH infrastructure installations; provide access to land, infrastructure, and waste streams; smart DH system connection mandates and compatibility requirements; development cost charges [16].

Currently, the problem is that policies supporting accelerated market penetration of smart DH systems are not implemented to their full potential [19]. Therefore there is a great need to analyze how different policy instruments influence local, regional and national energy systems. In the same way it is of great importance to study how policy frameworks and instruments at the urban level should be designed to stimulate and support an extension of sustainable thermal systems.

4.1.3. Mapping the stakeholders

It is vital for the success of the smart DH replication initiative that stakeholders (organisations and individuals) are mapped as early as possible in the process and that their roles in the preparation process as well as implementation process are identified after which the partnership agreement is signed with them. Effective engagement and involvement of the stakeholders will be critical to succeed with the process as well as it will be necessary to ensure good communication between stakeholders.

The challenge concerning the stakeholders is in the number of stakeholders that are involved in the planning process with an emphasis on exploiting waste heat potential from industrial sites or including demand side measures in the concept. Increasing the number of stakeholders implies a higher complexity in the planning task, more difficulties to access data and many private economic interests to satisfy so that should be taken into account during the mapping of the stakeholders [19].

Important stakeholders that have to be included in the preparation and implementation processes of smart DH systems in smart energy systems as well as examples of their roles are shown in Table 2.

Table 2. Stakeholders to be involved when developing smart district heating systems [19]

Stakeholder	Role
Politicians (including mayors)	Lead strategy
City administration	Implement roadmap
Utilities, energy service companies, network operators	Offer solutions
Developers, planners, architects	Connections of buildings to the network
Construction companies	The construction of power plants, installation and extension of thermal networks, refurbishments of buildings etc.
Inhabitants	Heat producers and/or heat consumers
Companies	Heat producers and/or heat consumers
Industries	Heat producers and/or heat consumers
Component manufacturers (windows, facades, pipes, HVAC components, etc.)	Technology providers
ICT companies	Technology providers
R&D institutes and universities	Technology providers
Renewable energy industry (heat pumps, geothermal, solar-thermal, etc.)	Energy suppliers
Financial institutions	Project development enablers

4.1.4. Information gathering

Gathering the information that is necessary to plan the smart DH system in a smart energy system is an important step that has to be done in order to analyse that information and propose the best measures to transform the heating system of a city into a smart DH system of a smart city.

Data has to be collected and organised in order to be used in evaluating the heating sector of the municipality. Important data for smart DH systems can be divided into three sets as follows:

1. Energy data of the municipality which includes heat production, heat consumption, heat losses, heat production efficiency, waste heat etc.
2. Climate and geographical/geological data of the municipality which includes wind speeds, solar irradiation, ground temperatures, nearby water temperatures etc. which makes the basis for calculating the RES potentials
3. Technical data of the municipality's heating systems which includes current heat production technologies, heat sources, distribution technologies, system temperatures etc.

Not all data is accessible to planners, so all the stakeholders should be included in providing the data. The official data available on a municipal level will vary depending on the municipality and on the country in question. Not every country has official statistics on a municipal level, but it should be researched what kind of official energy, climate and technical data are available.

Availability of various levels of data on energy use is reliant on the structure of energy markets and regulation. As municipality may not have a direct observation of data, energy data can also be provided by some utilities, as formal partners of the project. While building up a picture of current energy use, these records will be indispensable. Municipality may also not disclose certain amount of data as they may be considered ‘market sensitive’. Release of data required may well be facilitated by coordinating confidentially agreements with energy companies, network operators, fuel suppliers etc. Disclosure of data may also be possible only at a regional or national level. If so, the use of a top- down approach can help the accounting procedure, starting from the upper territorial level and using proxy variables to estimate the local level data.

4.1.5. Information analysis

After all the relevant information has been gathered, as described in the previous subchapter, the next step is to analyse this information in order to get a clear picture of the municipality's current heat sector situation and how developed and sustainable it is which gives the basis for proposing the measures that have to be implemented in order to develop the smart DH system in a smart city. This step represents a crucial part of the methodology since the measures and actions are proposed based on the information analysis.

By analyzing the heat consumption of end-users, the heat demand mapping can be done. This gives a clear picture of current state of buildings as well as of the end-user behavior. Also, this locates areas with highest potentials for smart DH systems as mentioned before.

By analyzing climate information on renewable energy sources, potentials for their utilization can be determined. For better analysis, the gathered RES data should be put on a map by the means of GIS tools. The locations of potential plants can then be much easier determined. Data of excess heat production in the municipality should also be mapped for the same reason. Also, the assessment of land (public or private) that is available for installation of smart DH related systems should be made.

By analyzing technical data of the municipality’s heating system, as well as the municipality’s energy data, current state of the heating system is determined. That way it can be defined what parts of the city are already connected to the district heating system as well as which improvements have to be made in order to transform the system into a smart district heating system.

In this step, after all the data is analyzed, it is also important to make models of current system and develop different 100% RES scenarios for the heating system in order to determine what are the best, most cost-effective measures that have to be implemented. Feasibility analysis of different scenarios (i.e. different measures and actions being implemented) has to be done in this step of the methodology. The capital, operational and maintenance costs, along with likely revenues from heat, cooling and electricity sales, should be roughly estimated at this stage. Here it will be appropriate to use a more sophisticated financial appraisal methodology, such as whole-life costing, that takes account of future cashflows and discounts them to present-day values. This will help to establish whether the proposed scheme is economically viable, and affordable for customers.

Things that have to be taken into account when making a feasibility analysis for smart DH system are space heating and domestic hot water loads; phasing of the development (for new-build projects); optimum route and size of pipes for the network; locations for plant room(s), length of network, height of buildings, local topography; network heat losses; type and scale of connections; thermal storage; data on load curves, base and peak loads; types of fuel and supply chains; space for delivery, storage and handling of bulky fuels; and other heat production opportunities that could augment the project. The analysis will result in a robust conclusion on the viability of the proposed district heating network including the economics, and will give all the technical information necessary to move onto the procurement process [54].

Different modeling tools can be used for that purpose and some of them will be defined and elaborated in the next chapter of this thesis. This is the step in which technical experts have to be involved i.e. experts from within the community, utilities, university experts, state agency assistance, and consultants.

4.1.6. Best practice analysis

In order to replicate a smart DH system into a smart energy system of a smart city, it is fundamental to define what are currently the best examples that can be implemented in a certain city. Municipalities that have certain experience with the implementation of smart DH system have to be defined. Since the world is becoming a smaller place and everything is getting more strongly connected, in the future it will take much less effort to determine the good practices of other cities.

However, due to the fact that smart energy systems as well as smart DH systems are new concepts, there are currently no completely developed smart DH systems, although there are projects that are under way and which will lead the way towards dissemination of such concepts. For example, the smart DH systems in the city neighborhoods in Tartu, Sønderborg and Vitoria-Gasteiz will be completed by 2020, which will result in a number of best practices from these projects ready to be replicated [43].

When determining the best practices that are currently available, important aspects for replication have to be taken into account as mentioned earlier in this thesis. All the aspects important for replication have been identified in Chapter 3 of this thesis.

4.1.7. Proposing actions and measures

After all the information as well as best practices have been analysed, it can be decided which measures and actions will be implemented in the given city to achieve a smart DH system as a part of a smart energy system. The technical, financial and institutional limitations described in Chapter 3 will determine which measures and actions are good enough to be implemented. Sets of measures and actions are than proposed for buildings, residential homes, heating infrastructure, utilities etc. The scale and design of smart thermal grids will depend on the urban density of the districts. For that reason, different capacities of the plants will be implemented for different urban scales. For small scale urban areas, which can be defined for around 30 000 people, overall capacity of the plants should be 50-70 MW_{th}; for medium scale urban areas (around 400 000 people), overall capacity of the plants should be 750-850 MW_{th}; for large scale urban areas (1 000 000 people), overall capacity of the plants should be 1 900 000-2 100 000 MW_{th} [19]. These needed capacities are much lower than for the traditional DH systems, e.g. installed capacity for Zagreb DH (serving 86 358 households which equals to around 250 000 people) is 1420 MW_{th} [42].

Some off-grid systems will have to complete the system since smart DH network cannot cover the whole municipality

The priority of measures as well as the time span for each measure should be determined. For example, when it comes to refurbishing existing buildings, renovation of public buildings should have priority in order to demonstrate advantages of such a measure to other stakeholders.

4.1.8. Determining financial framework and proposing implementation plan

Now that all the actions and measures to be implemented have been determined, the costs of the implementation process can be defined. Having clearly defined costs is vital in order to determine financial means, which the municipality commits itself to distribute from its overall budget, as well as the means that are expected to be achieved from external sources, which will overall be used for the implementation process. Assessment and recognition of financial risks of the implementation plan is essential, along with actions for local capacity building on financial matters. Each stage of the process must be financed and as such there is a progressive increase in costs. However, as the project progresses the risk of project failure decreases.

All of the costs related with the effective implementation of each action must be distinctively described in 'financing plan', all the while accounting for the agreed timeframe. Contingency resources finance and time should be included to allow for unmanaged risks.

Guarantee of compensation for any delays or unexpected costs will be entailed by some actions. Required resources should be allocated within the annual budget by the municipality while making the commitment in the forward planning budget.

During the preparation process, constant monitoring and reporting of progress should be done to give feedback on meeting deadlines for every step and assessing the achieved results. Lots of plans have failed due to a lack of reporting and monitoring procedure. Good monitoring plan should be developed in advance; otherwise it will pose a very difficult task. Indicators should be developed to monitor the steps more easily.

After all the previously mentioned steps of the preparation process have been made, an implementation plan should be proposed which should include all the actions and measures that have been proposed along with costs, revenues, financing, time frames and the business plan for the project.

The plan should also specify which stakeholders are in charge of which actions, how are actions and measures going to be implemented and basically giving the answer to questions what will be done, why will it be done, how will it be done and by who will it be done.

All the previous steps of the methodology that were mentioned are a part of the preparation process of the project, after which the implementation process is being conducted.

4.1.9. Implementation

After the preparation process has been successfully finished, proposing feasible solutions that should be implemented in a city, the implementation process commences. The implementation process will differ depending on the city in question so this part will not be elaborated in detail. One of the proposed scenarios for implementation of smart DH systems is given in [19] and consists of the following steps:

1. Acquiring necessary licenses, permits and authorization
2. Construction, installation and extension of smart DH technologies
3. Testing prior to start of operation

The implementation process as defined by [19] starts with acquiring necessary licenses, permits and authorizations, which are depending on the RES technologies being implemented and the size of the project. Environmental impact assessment is mandatory by legislation, but full one is required only for big projects. This part of implementation process should take up to one year to be completed.

After all the permits have been granted, construction, installation and extension of the smart DH technologies take place at previously determined locations. Construction companies are in charge of construction of power plants, installation and extensions of thermal networks and renovation of buildings, which also takes place in this step.

First construction steps should be well publicized and well reported so that there are visible achievements early on. That helps to improve the progress of the project. Due to the complexity of this step, the predicted time span for this part of the implementation is up to two years [19].

The last part of the implementation process is testing of the facilities prior to start of operation. This part usually takes up to one year [19].

4.2. Replication flowchart

Now that all the important steps for replication of smart DH system into a smart energy system have been presented and elaborated, a replication flowchart can be drafted. A flowchart can be defined as a type of a diagram that serves as an algorithm, process or a workflow. It shows the steps that have to be made as different boxes and connecting the boxes with arrows shows their order.

Flowcharts illustrate a solution model to a given problem. They are used in analyzing, managing, documenting or designing a process or program in various fields. As all the other types of diagrams, they help visualize actions that are taking place hence helping better understanding of the process.

All the main necessary steps for replication of smart DH system have been described in the previous subchapters so they can be graphically presented in the form of the flowchart, actually representing the model for replication of smart DH system in a smart city. The replication flowchart is shown in Figure 18. The lighthouse city represents a city whose system is being replicated.

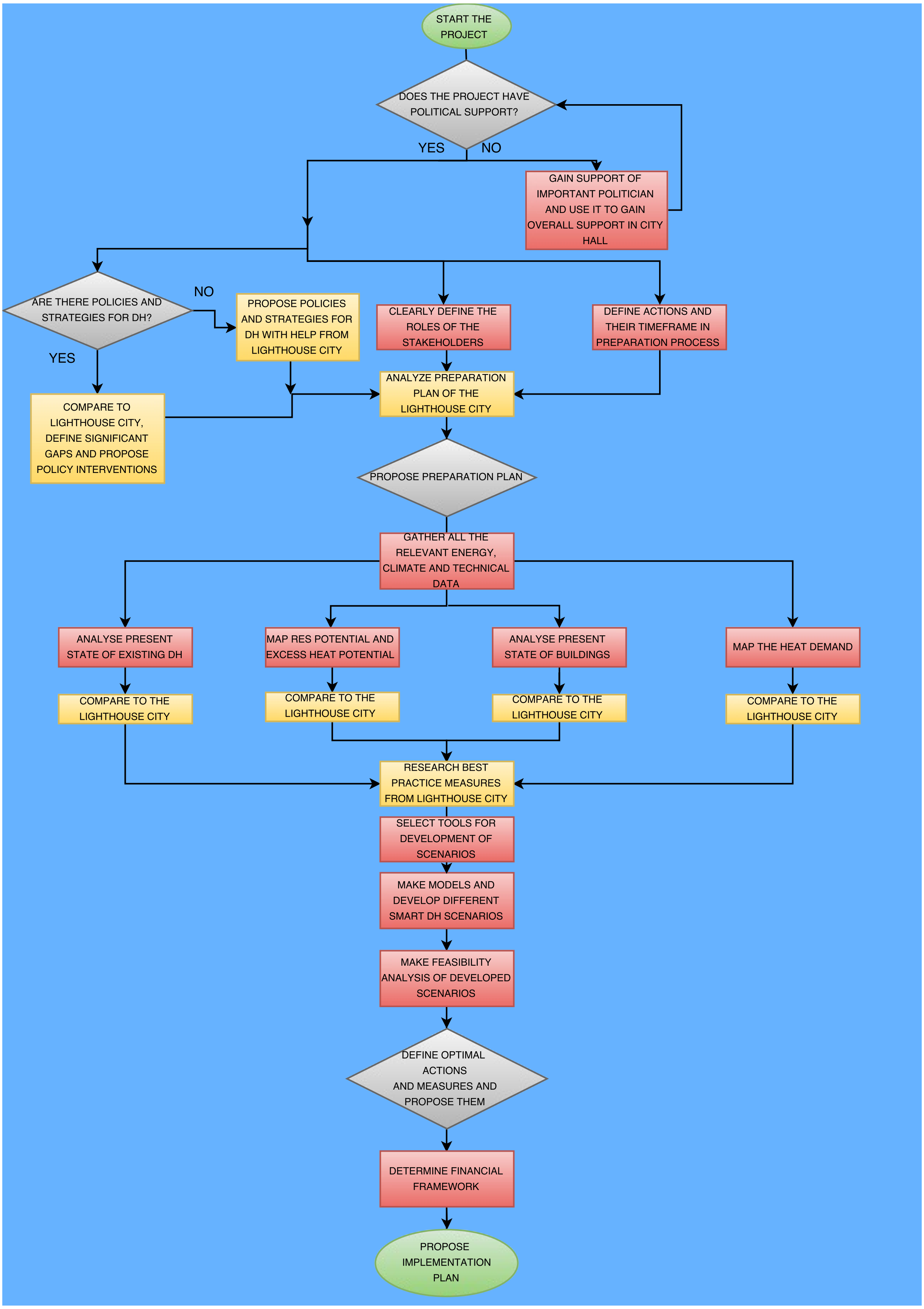

Figure 18. Replication flowchart

5. TOOLS AND METHODS FOR INDIVIDUAL REPLICATION IN SØNDERBORG

In this chapter, already available tools that might be used during the implementation of replication and scaling-up plans in the city of Sønderborg as the part of the SmartEnCity project will be defined and discussed. Tools that are proposed for the project and that are going to be discussed are: energyPRO, Termis, NetSim and C.a.R.D.I.F./I.H.E.N.A.

One of the most widely used tools for modelling of smart energy systems is EnergyPlan software which has to be mentioned here but will not be described along other softwares since it was already described in detail [55] and is used for modelling on a national or regional scale rather than city or municipality level.

Brief description of the city of Sønderborg as well as its demonstration activities in the smart DH area will be given prior to discussion of tools. In this chapter, content of individual replication roadmap for smart DH system of the city of Sønderborg will also be proposed.

5.1. City of Sønderborg as a part of the SmartEnCity project

The city of Sønderborg is located in the Region of Southern Denmark and is a part of Sønderborg municipality. It is the capital and administrative seat of the municipality. The total area of the city of Sønderborg is estimated to have 10 000 residents, while the municipality has around 75 000 residents. The climate of the city is considered as temperate oceanic climate in a bordering area with colder climate. The position of the city of Sønderborg in the map of Denmark can be seen in Figure 19.

The demonstration area for smart DH system implementation is inner town area of Sønderborg, around 4 km^2 in size with approximately 1700 residents. It contains different types of residential buildings, mainly older residential brick buildings from 1950-1960's and social housing building blocks typically with 2-4 storeys built as concrete elements. The total of 45 buildings (all of them being residential buildings) will be renovated in demonstration activities with heat for all of them already supplied by the Sønderborg District Heating Company. Buildings to be included in the project are selected according to the retrofitting plans of the involved social housing companies, therefore making implementation and financing more feasible as already discussed in Chapter 3 of this thesis. All the demonstration buildings are owned by social housing companies.

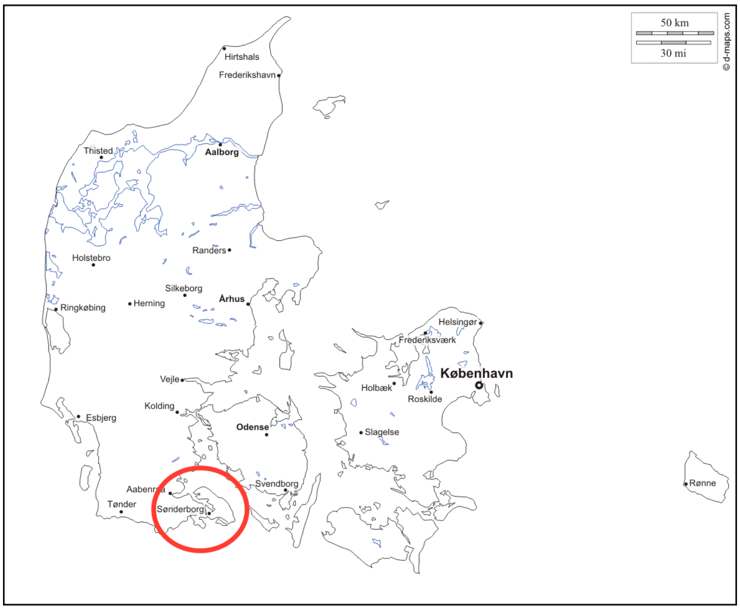

Figure 19. Position of the city of Sønderborg in Denmark

Proposed specific measure regarding the thermal energy consumption of buildings in demonstration areas of Sønderborg is installation of new, more efficient automatic-on heat exchangers, as well as other measures like insulation of outer walls, new low energy windows and doors, insulation of roof, new ventilation system with heat recovery depending on the building in question. Joint implementation of these measures, including improvements to the DH system are expected to significantly decrease energy consumption and carbon footprint of retrofitted buildings. Overall expected energy savings in retrofitted buildings are 72 kWh/m^2 per year.

The mix of energy sources that are used in Sønderborg DH system vary from year to year but it can be concluded that on average, 50 % of supply is estimated to be covered from natural gas co-generation unit and 50 % from local RES, including solar thermal, geothermal and biomass. It is planned to implement a 5 MW heat pump (COP is 4 and the heat source is sea water) in order to replace gas-fired CHP plant. This heat pump will cover 75-80 % of heat demand for the city of Sønderborg. It is expected to produce around 170 GWh per year.

The rest of the heat demand will be covered by existing geothermal and solar and eventual new biomass thus covering 100 % of heat demand with RES. Backup for the heat pumps will be electric boilers which will use electricity from nearby offshore wind park. The large scale heat pump will also use electricity from the wind park, being directly linked to it and therefore enabling delivery of RES electricity free of taxes. Overall expected CO_2 reductions from implementing 100 % RES in DH system are 43 tonnes per year.

5.2. energyPRO software

energyPRO is a software which was developed by Henrik Lund in the late 1980's and made commercial in collaboration with EMD International A/S, Danish software and consultancy company within the field of project design, planning and documentation of environmental friendly energy projects [56].

It is a modelling software which is used primarily for modelling district heating systems in order to perform an integrated detailed technical and financial analysis, both for currently existing DH systems and for the new DH projects. It provides a clear overview of the project for the user and has a very user-friendly interface.

It can be used in variety of district heating projects, e.g. cogeneration plants with gas engines combined with boilers and thermal storage, industrial cogeneration plants supplying both electricity, steam and hot water to a site, cogeneration plants with absorption chilling (trigeneration), biogas fuelled CHP plants with a biogas store, biomass cogeneration plants as well as other types of projects [56].

energyPRO software is based on a modular structure, which enables carrying out different types of analyses. There are seven modules in the energyPRO software. The tool can be bought for €2700 to €5600 depending on the modules chosen. Design module, is the basic module used to calculate optimal conversions for heat, cooling and electricity in a one-year period. Finance module expands energy and economic calculations to cover the projected lifetime of the project. Accounts module allows users to generate income statements, balance sheets for each year in project period and taxation models. Operation module is used to plan the optimal production from energy plant for days or weeks ahead.

Region module includes facilities to de ne multiple sites within a region in which demands and production units are geographically separated. Markets module makes analyses and optimization of CHP plants with simultaneous participation in different electricity markets (e.g. day ahead, reserve and balancing markets). Interface module allows specifying changes in several projects without having to do that in each individual file [56]. An example of interface of modules is shown in Figure 20.

Figure 20. Interface of different energyPRO modules; design module (up) and accounts module (down) [56]

The energyPRO model is basically a deterministic input/output model for calculating annual productions in time-steps of typically 1 h. Inputs are capacities, efficiencies, and the hour-by-hour distribution of heat demand and electricity sales-prices. Model includes examples of input data, which makes deriving new data sets from examples very easy. It also accounts for all system costs along with SO_2 and NO_X penalties.

It can be highly customized, and has direct access to databases for ambient conditions. This enables a very detailed modeling process, since it allows the software to simulate actual weather conditions, which is vital for analyzing energy conversion units using intermittent energy sources.

Optimization period is divided into calculation periods, where variables are constant (e.g. priorities, solar radiation, heat demands, electricity demands, cooling demands, production capacities and fuel deliveries). The calculation periods can be divided into groups, typically groups in which electricity prices are the same. A priority name, e.g., Peak Load, High Load or Low Load, designates each group [57].

Instead of calculating the energy productions in a chronological order, the software calculates, productions of the most favorable periods for the whole year, as those are determined in the operation strategy. The operation strategy can be user defined or auto calculated and is a decision table used to describe the priority between energy production units in different tariff periods. As a consequence, before being accepted, each new planned production is carefully checked so that it will not disturb already planned productions with higher priorities. The non-chronological production is an advanced capability that none of the similar software tools have [57].

It should be noted that the computational methodology of the energyPRO software depicts the optimal operation of CHP plants. Consequently, the results of the analysis regarding the optimum plant design, using this software tool are only valid to the degree in which the operation manager of the plant is able to achieve such operational performance in practice.

In order to use energyPRO software, one day of training is necessary and there are more than 1000 users of the software in 16 countries [55]. Many analyses have already been done using that software. In [57], authors have performed optimization of small CHP plants in a competitive market of Lithuania by using energyPRO. It is also used in [58] where authors explore the most economic size of gas engines and thermal storage in case of CHP plants aggregation. In [59], the energy system is modeled by the means of energyPRO in order to investigate how different storages (including district heating storage) marginally affect the amount of wind power that may be integrated applying the different storage options and the associated economic costs.

5.3. Termis software

Termis is an advanced software for real-time planning and optimization of district heating and cooling network operations. It is developed by Schneider Electric, an international company specialising in energy management.

Termis is considered to be the most advanced, powerful and extensive district energy network simulation tool for making improvements in system design and operation. It enables control and gives overview of district energy network by simulating thermal behaviour, flow and pressure of the network. The software can be used for planning purposes and for evaluating the network performances or design alternatives [60].

The user interface can be customized to suit the individual needs and requirements of the many types of users. By using the intuitive button interface, data for pressure, thermal conditions and flow can be obtained at any given time i.e. present, past and future.

Termis allows viewing of different areas, sections, zones, and even details of the network. User can easily simulate interventions such as supply changes, opening or closing of valves, starting or stopping of pumps and plant, and assess the impact on consumer supply. Data flow of the software is shown in Figure 21.

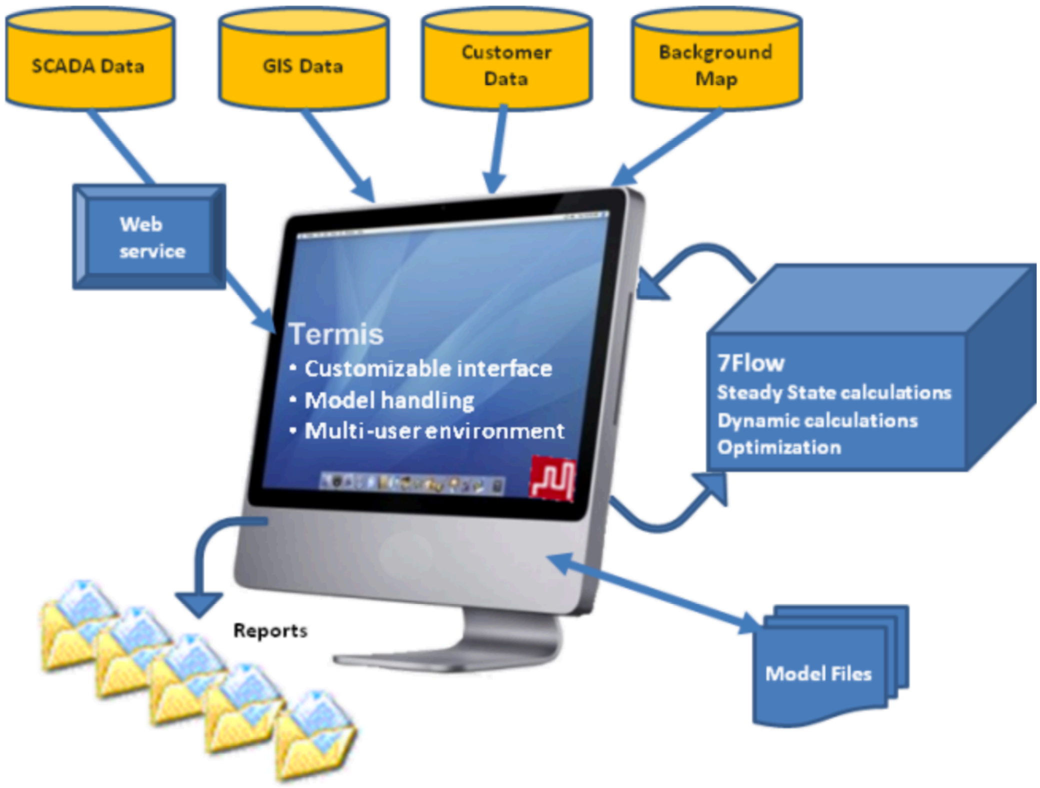

Figure 21. Illustration of data flow in Termis [61]

The use of Termis software enables the user to [61]:

- Import network data with consumer information from external data such as Geographic Information System (GIS).
- Create and edit network information
- Perform hydraulic simulations for design studies
- Display simulation results as thematic views, profiles, and time series
- Generate reports
- Export data for external analysis

The real time version of the software is in use in over 500 district heating systems in the world in connection with Supervisory Control And Data Acquisition (SCADA) systems.

Termis software has been used in a number of district heating analyses. Some of the cases are defined sa follows. In [62], authors performed a case study of the annual energy performance of a low-energy network for low-energy houses in Denmark. Termis was used for a year simulation of different cases.

Furthermore, in [63], opportunities and challenges of implementing low-temperature district heating with RES solutions in Canada, with focus on the network design and operation were analyzed. The simulation models were developed using Termis software. Network dimensioning was also carried out in Termis by steady-state simulations. In [64], authors presented a method for the design of a low-energy DH system, concerning the studies of different pipe dimensioning methods, substation types and network layouts. The optimal pipe dimensions found were evaluated by use of the Termis software with input of several randomly generated heat demand scenarios involving peak winter conditions.

Also, in [65], authors studied the effect of bypassing DH water during non-heating days to the bathroom floor heating instead of to the return pipe (which results in losses). The effect on the DH network was investigated using Termis software

5.4. NetSim software

NetSim software is a commercial calculation and simulation program that simulates technical parameters in district heating and district cooling networks. It can perform accurate grid calculations considering different parameters. It is developed and sold by Vitec, a software company that offers industry specific business applications on the Nordic market.

It is used by over 55 energy and consultancy companies in northern Europe (Sweden, Norway, Finland and Denmark). NetSim software is based on the simulation tool LicHeat, from which the previously described Termis tool was also developed. The technical parameters that can be analyzed in NetSim software are supply temperature, return temperature, differential pressure, pressure in the supply and return pipes, flow rate, velocity, heat power and pipe losses. NetSim includes a powerful graphical interface which is used to define the pipe networks and calculation criteria, an effective calculation drawing module, a powerful graphic presentation of calculation results in the form of charts, diagrams and tables, powerful export tools which directly export data to Excel format, DXF/DWG and a number of raster formats and powerful import tools for importing data from a number of network information systems on the market [66].

An overview of input values and resulting output values from NetSim software is illustrated in Figure 22 [67].

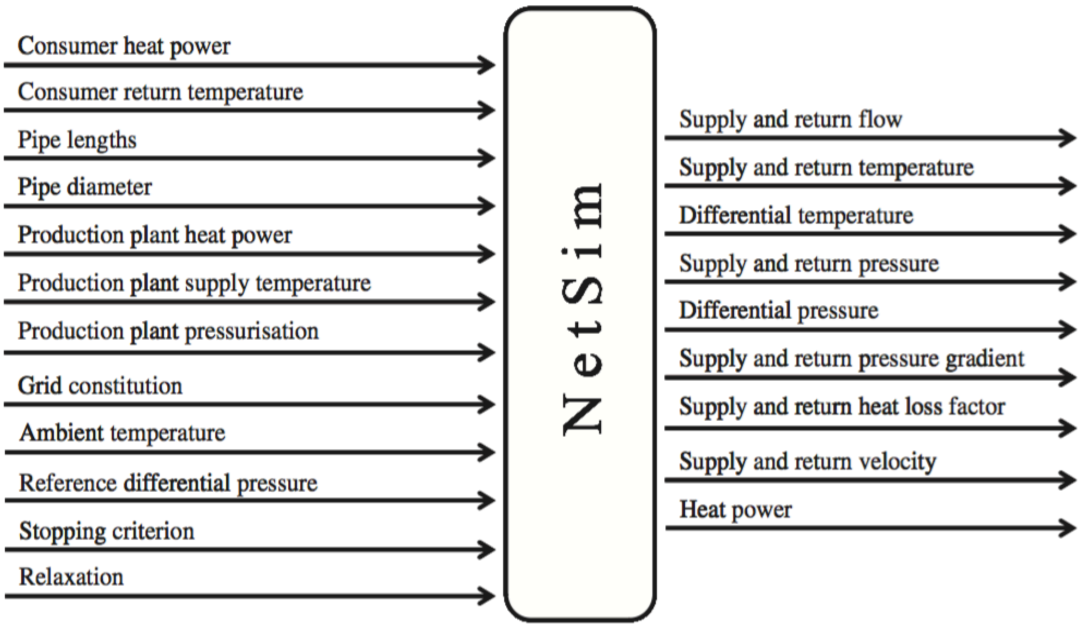

Figure 22. Input to and output from NetSim software [67]

A pipe network can be drawn manually or imported as a CAD file and the software can perform sizing calculations such as dimensioning of pipes and also dynamic calculations to simulate changes of network temperatures. The network calculation model consists of nodes and pipes which are the basic elements of the model and all the numerical information is linked to these elements. Nodes are represented as circles on a chart while pipes are represented as a line between the nodes [66].

The simulation of network in NetSim can be done in three levels. In level 1 all the pipes are included, in level 2 only the primary and secondary pipes are included and in level 3 only the primary pipes are included. When the higher levels are used, the heat powers in the nodes on the smaller pipes are collected in the nearest node on a bigger pipe. The higher levels are primarily used when simulating larger networks, since this would otherwise be very time consuming [67].

In order to compensate for pressure losses in DH network caused by turns in the network, valves, welded joints etc., the roughness for pipes that is used in NetSim simulations is higher than what the real values would be. Considering the dynamics of the system, NetSim can perform both static and dynamic simulations. Static simulations calculate technical parameters when the district heating network has reached stationarity for the specified input data. Dynamic simulations show how the technical parameters vary over a period of time. The longest time period that is possible to simulate is 24 h. Dynamic simulations require more detailed input than static simulations [67].

Resulting data from NetSim simulations can be presented in following forms:

- Graphs
- Charts
- Fly outs
- Color maps
- Timelines
- Max/min values

In the simulations, NetSim also demands a stopping criterion and relaxation for the iterations. The values for stopping criterion are recommended to be set to 0.005 and for the relaxation to be set to 0.5.

Most studies conducted with NetSim that are found in the literature are made for impact of prosumers on smart DH networks. For example, in [67], the technical impact of small-scale local solar collectors and heat pumps (prosumers in smart DH networks) on district heating distribution networks is investigated with simulations mainly being done by NetSim software. Furthermore, in [68], more calculations of technical parameters in DH pipes were carried out by NetSim in order to continue researching both the technical and environmental issues connected to an introduction of prosumers into the DH network. In [69], a case study was conducted on impact of prosumers on DH networks for an area under construction in Malmo, Sweden. Again, NetSim was the software used for making environmental calculations.

5.5. C.a.R.D.I.F./I.H.E.N.A. software

Both C.a.R.D.I.F and I.H.E.N.A. software were developed at University of Bologna for simulating the behaviour of DH network under given conditions. It can be said that I.H.E.N.A. is an upgraded version of C.a.R.D.I.F.

5.5.1. C.a.R.D.I.F. software

C.a.R.D.I.F. software is written in VBA language and it can be used for the analysis of a DH network by simulating its behavior or for the design by defining a DH network and starting a trial and error procedure. Software is based on a Todini-Pilati algorithm. The working of this software can be best shown by the means of the flowchart as presented in Figure 23.

In order to better understand the flowchart, variables shown in the flowchart should be defined. A_{11} is a diagonal matrix, A_{21} is a topological matrix where the rows of the matrix represent the nodes of the network and the columns represent pipes and A_{12} is a transpose matrix of A_{21}. Furthermore H represents energy content of the liquid in a node, ΔH represents the pressure losses through the pipes and Q represents the mass flow rate. Detailed explanation of Todini-Pilati algorithm is presented in [70].

Input parameters are defined as follows: Geometrical input (Cartesian coordinates (x, y, z) for each node, inside and external diameter of each pipe including the insulating material, length of the pipes, pumps position and operational characteristics etc.; in this section also the nodes typology can be defined); Utilities input (thermal power required by each of the defined utilities and/or the required mass flow rate, temperature difference between the inlet and the outlet of the primary utility circuit, etc.); Sources input (number and position of sources, supply pressure, supply temperature, pressure of the expansion vessel, pump system operational characteristics and performance, etc.); Pipe parameters (conduction coefficient of each pipe, roughness, conduction coefficient of the insulating material, etc.).

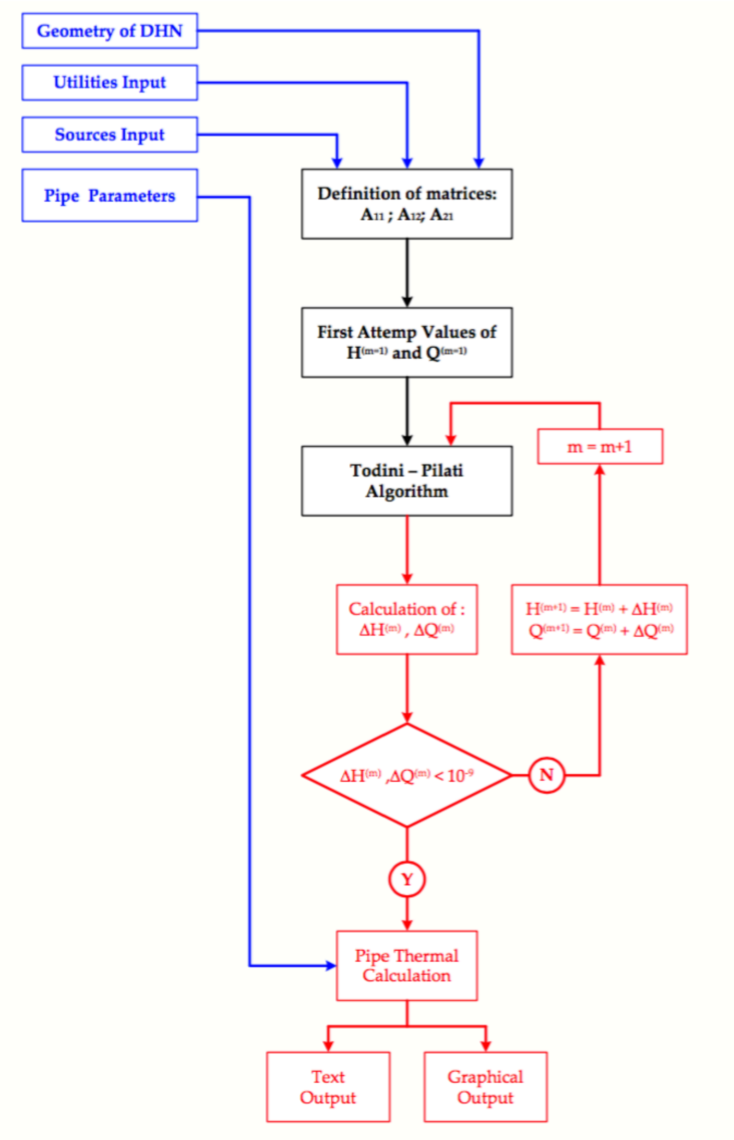

Figure 23. Main calculation code flowchart of C.a.R.D.I.F. software [70]

Those inputs have to be defined for supply as well as for the return pipes. Once the supply layout of the network has been defined in the software, the return layout is also defined simply by reversing the direction of the flow. Thus, the nodes that are sources for supply are considered as utilities for return. In the same way, the utilities are considered as sources, while the mixers remain the same. With this approach, the flow chart in Figure 23 can be used for both "*supply*" and "*return*" calculation.

Outputs of the software, both for the supply and return of the DH network as follows: inlet and outlet temperature and pressure, mass flow rate, velocity, pressure drop for each pipe, total mass flow rate supplied from the sources, total electrical power for the pumping stations and pressure drops at each of primary circuits of the utilities. The software enables visualization of DH network's layout with indicators of flow direction on each pipe. C.a.R.D.I.F. makes it possible to calculate and graph the distributions of velocity, mass flow rates, pressure losses and diameters. User can understand the representation immediately since different colors are used for the different ranges of the considered quality [70].

5.5.2. I.H.E.N.A. software

I.H.E.N.A. software has also been developed on University of Bologna and its main aim is to evaluate the performance of smart DH networks. Its calculation code has also been based on Todini-Pilati algorithm generalized by the use of Darcy-Weisbach equation and it actually represents an evolution of the C.a.R.D.I.F. software in order to take into account the bidirectional exchange of thermal energy with reference to different substation schemes. I.H.E.N.A. software can be used both for the design of new networks and optimization and performance analysis of the existing ones. The flowchart of the software is given in Figure 24 [71].

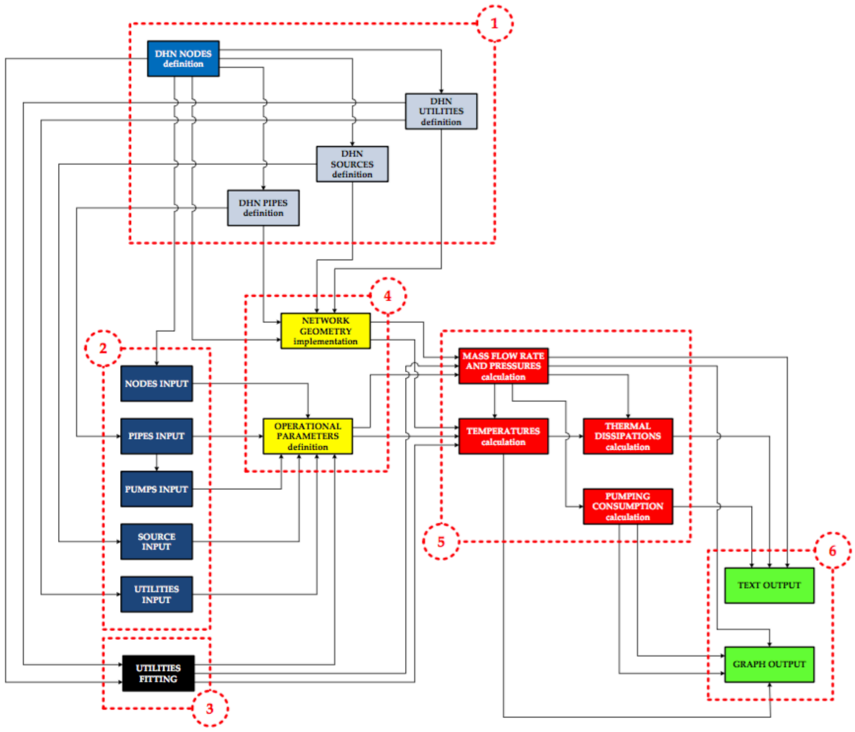

Figure 24. Main flowchart of I.H.E.N.A. software [71]

Six different sections that are defined in the flowchart are as follows:

1. Network implementation – Geometry layout of the network is defined in this section
2. Network input – Introduction of the main network input (characteristics of sources and utilities)
3. Utilities fitting – The first attempt of the solution calculation, in terms of the balance between the decentralized thermal production, the utility needing and the network feeding
4. Network geometry implementation and operational parameters definition - Drawing of the network and definition of regulation strategy
5. Network calculation – By using the Todini-Pilati algorithm, temperatures, pressures and mass flow rates are calculated
6. Text and graphical output – The output in both text and graphical form is written

Input parameters were already described for the C.a.R.D.I.F. software as well as the outputs. Those parameters are the same for I.H.E.N.A. software.

5.6. Content of Replication Roadmap for the city of Sønderborg

As one of the tasks in Workpackage 8 of SmartEnCity project, it is necessary to develop replication roadmaps for each lighthouse city.

Roadmap describes how to get from the current state of the heating system to the smart DH system with intermediate targets and milestones and the means and measures for reaching them. Its objective is to codify the project results and lessons learned and make them available to wider scale effective use and exploitation.

In order to make it easier for stakeholders that will be working on the development of replication roadmaps, the content of such a roadmap will be proposed in this chapter. The content will be proposed for the city of Sønderborg.

Based on previous chapters in this thesis, main chapters for individual replication roadmap of the city of Sønderborg are proposed as follows.

- Introductory part – description of smart DH system characteristics, advantages, why is it needed, etc.
- Evaluation of local present state conditions – evaluation of the current heating system, local RES and excess heat potentials, evaluation of the current state of buildings
- Evaluation of possible obstacles for replication – definition of obstacles as described in Chapter 3 of the thesis (technical, financial, institutional)
- Definition of requirements needed to ensure the proper replication – proposing the solutions to eliminate the obstacles for replication
- A list of deployable solutions to be focused in the rest of the city – defining which of the solutions already implemented can be used in the rest of the city
- Definition of milestones during the replication process – defining important events in the replication process as already done in the lighthouse project
- Financial plan for ensuring the replication of innovative solutions – proposing the financial plan by making the analyses of the existing financial plan for implemented measures

6. CONCLUSION

In this thesis, several tasks were performed. First of all, an overview of demonstration activities in the field of smart cities was performed in order to define lessons learned from those projects. This will serve as a useful input in SmartEnCity project. The main lessons learned from three demonstration activities already performed in cities in Brasil and Netherlands and 45 ongoing demonstration activities in cities all over the world could be summed up as: engaging citizens to be actively involved in projects, which is already clearly outlined in SmartEnCity project; technologies that will be used by the end-user must be easy to use; projects must have a strong political support, with local governments being the most important stakeholder in catalyzing investment in district energy systems; roles of each stakeholder and the expected results must be clearly defined in order for the project to succeed.

The next task was to define characteristics of smart DH systems and state-of-the-art smart DH technologies. Although there are currently no completely developed smart DH systems, there are some rather advanced systems incorporating smart features to certain extent. After a comprehensive review of literature concerning the state-of-the-art smart DH has been done, it can be concluded that all the technologies for smart DH systems already exist and can be incorporated, although some of the technologies, mainly smart heat meters, seasonal thermal storage and cascade energy usage are still not feasible to be used in a large scale, requiring further developments. However, it is expected that significant developments of DH technologies will take place in the future, which will play an essential role in the operation of smart energy systems

In order for a smart DH system to be replicated in a city, different aspects should be considered. Four of the most important aspects (geographical, financial, technical and ownership) for replication have been defined and elaborated in this thesis. Bearing those aspects in mind, a methodology for replication of smart DH systems was developed defining and describing important steps that have to be done in order to replicate such a system in other cities. The result of methodology development is a replication flowchart.

Finally, four tools for modelling and simulating operation of smart DH systems have been defined and described. Tools being described are energyPRO, Termis, NetSim and two softwares from University of Bologna I.H.E.N.A. and C.a.R.D.I.F.

These tools were just briefly described, without making any tests on them so it cannot be really concluded which of these tools would be the best for modelling of a smart DH system during the replication process. Due to the smart DH requirements it can be stated that the most suitable tool would be I.H.E.N.A. software since it is designed specifically for smart DH systems but its drawback is that it is not commercially available. Also, the content of Replication Roadmap for Sønderborg is proposed in order to make it easier for stakeholders that will be working on the development of replication roadmap for Sønderborg.

REFERENCES

[1] "International Research Centre of 4th Generation District Heating," 2016. [Online]. Available: http://www.4dh.dk/. [Accessed: 11-Jan-2016].

[2] "Cities and Climate Change," *United Nations Environment Programme*. [Online]. Available: http://www.unep.org/resourceefficiency/Policy/ResourceEfficientCities/FocusAreas/CitiesandClimateChange/tabid/101665/Default.aspx.

[3] "Statistics on European Cities," *EUROSTAT*. [Online]. Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Statistics_on_European_cities. [Accessed: 01-Nov-2015].

[4] "European Innovation Partnership on Smart Cities and Communities," 2015.

[5] A. Khare, T. Beckman, and N. Crouse, "Cities addressing climate change : Introducing a tripartite model for sustainable partnership," *Sustain. Cities Soc.*, vol. 1, no. 4, pp. 227–235, 2011.

[6] B. V. Mathiesen, R. S. Lund, D. Connolly, I. Ridjan, and S. Nielsen, "Copenhagen Energy Vision: A sustainable vision for bringing a Capital to 100% renewable energy," Department of Development and Planning, Aalborg University, Copenhagen, 2015.

[7] "Intelligent Energy Systems and Active Networks," 2015. [Online]. Available: http://www.et.aau.dk/research-programmes/intelligent-energy-systems-and-active-networks/.

[8] P. D. Lund, J. Mikkola, and J. Ypy, "Smart energy system design for large clean power schemes in urban areas," vol. 103, pp. 437–445, 2015.

[9] B. V Mathiesen, H. Lund, D. Connolly, H. Wenzel, P. A. Østergaard, B. Möller, S. Nielsen, I. Ridjan, P. Karnøe, K. Sperling, and F. K. Hvelplund, "Smart Energy Systems for coherent 100 % renewable energy and transport solutions," *Appl. Energy*, vol. 145, pp. 139–154, 2015.

[10] C. Sundstr and M. Krysander, "Smart Energy Usage for Vehicle Charging and House Heating," *IFAC-PapersOnLine*, vol. 48, no. 15, pp. 224–229.

[11] H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J. E. Thorsen, F. Hvelplund, and B. V. Mathiesen, "4th Generation District Heating (4GDH)," *Energy*, vol. 68, pp. 1–11,

2014.

[12] K. Qvist, C. Jacobsen, and J. Iversen, "Ultra Low-Temperature District Heating With 35 °C Supply Temperature," in *International Conference on Smart Energy Systems and 4th Generation District Heating*, 2015.

[13] A. F. Sandval, E. Ahlgren, and T. Ekvall, "Assessing Impacts of a Regional Collaboration on Large-scale Excess Heat Utilization," *Int. Conf. Smart Energy Syst. 4th Gener. Dist. Heat.*, 2015.

[14] O. Gudmundsson, J. E. Thorsen, and M. Brand, "Cost of District Heating and Individual Heating Technologies," in *International Conference on Smart Energy Systems and 4th Generation District Heating*, 2015.

[15] J. Desmedt, D. Vanhoudt, and B. Claessens, "The Role and Potential of Distributed Thermal Energy Storage Systems for Active Control of District Heating Networks," in *International Conference on Smart Energy Systems and 4th Generation District Heating*, 2015.

[16] L. Riahi, "District Energy in Cities-Unlocking the Potential of Energy Efficiency and Renewable Energy."

[17] "Amsterdam Smart City." [Online]. Available: http://amsterdamsmartcity.com/?lang=en.

[18] "Smart city transformation: 5 lessons learned from a 'living lab.'" [Online]. Available: http://inform.tmforum.org/strategic-programs-2/open-digital/2015/08/smart-city-transformation-lessons-learned-from-a-living-lab/.

[19] R. R. Schmidt, N. Fevrier, and P. Dumas, "Key to Innovation Integrated Solution - Smart Thermal Grids," 2013.

[20] S. Frederiksen and S. Werner, *District Heating and Cooling*, 1st ed. Lund: Studentlitteratur AB, 2013.

[21] A. Eisentraut and A. Brown, "Heating Without Global Warming-Market Developments and Policy Considerations for Renewable Heat," Paris, 2014.

[22] R. R. Schmidt, O. Pol, D. Basciotti, and J. Page, "Smart thermal networks for smart cities – Introduction of concepts and measures," 2012, vol. 04002.

[23] H. Averfalk, P. Ingvarsson, U. Persson, and S. Werner, "On the use of surplus electricity in district heating systems," in *The 14th International Symposium on District Heating and Cooling*, 2014.

[24] B. V. Mathiesen, D. Drysdale, J. Fernández-Chozas, D. Connolly, I. Ridjan, and H. Lund, “A Review of Smart Energy Projects & Smart Energy State-of-the-Art,” Copenhagen, 2015.

[25] R. Wiltshire, Ed., *Advanced District Heating and Cooling (DHC) Systems*, 1st ed. Elsevier Ltd, 2015.

[26] H. Gadd and S. Werner, “Achieving low return temperatures from district heating substations,” *Appl. Energy*, vol. 136, pp. 59–67, 2014.

[27] H. Li and S. J. Wang, “Challenges in Smart Low-Temperature District Heating Development,” *Energy Procedia*, vol. 61, pp. 1472–1475, 2014.

[28] “EU Energy Policy Framework,” 2016. [Online]. Available: http://ec.europa.eu/research/energy/eu/index_en.cfm?pg=policy. [Accessed: 10-Jan-2016].

[29] “Climate:Europe.” [Online]. Available: http://en.climate-data.org/continent/europe/.

[30] “Nelson Institute - Center for the Sustainability and the Global Environment.” [Online]. Available: https://nelson.wisc.edu/sage/data-and-models/atlas/maps.php?datasetid=54&includerelatedlinks=1&dataset=54. [Accessed: 01-Dec-2015].

[31] S. Werner, “ECOHEATCOOL: The European heat market,” 2006.

[32] U. Persson and S. Werner, “Heat distribution and the future competitiveness of district heating,” *Appl. Energy*, vol. 88, no. 3, pp. 568–576, 2011.

[33] D. Connolly, H. Lund, B. V Mathiesen, S. Werner, B. Möller, U. Persson, T. Boermans, D. Trier, P. A. Østergaard, and S. Nielsen, “Heat Roadmap Europe : Combining district heating with heat savings to decarbonise the EU energy system,” *Energy Policy*, vol. 65, pp. 475–489, 2014.

[34] “Stratego:Advanced Heating and Cooling Plans.” [Online]. Available: http://stratego-project.eu/.

[35] B. Atanasiu, C. Despret, M. Economidou, J. Maio, O. Raph, and I. Nolte, “Europe’s buildings under the microscope,” 2011.

[36] “Europe’s onshore and offshore wind energy potential,” Copenhagen, 2009.

[37] “Performance guarantees constitute key element in district heating.” [Online]. Available: http://dbdh.dk/performance-guarantees-constitute-key-element-in-district-heating/.

[38] “Green Rhino Energy.” .

[39] A. Chittum and P. Alberg, “How Danish communal heat planning empowers municipalities and bene fi ts individual consumers,” *Energy Policy*, vol. 74, pp. 465–474, 2014.

[40] “Geothermal District Heating.” .

[41] B. Elbersen, I. Startisky, G. Hengeveld, M. J. Schelhaas, H. Naeff, and H. Botcher, “Atlas of EU biomass potentials,” 2012.

[42] D. Culig-Tokic, G. Krajacic, B. Doracic, B. Vad Mathiesen, R. Krklec, and J. Møller, “Comparative analysis of the district heating systems of two towns in Croatia and Denmark,” *Energy*, vol. 92, pp. 435–443, 2015.

[43] J. Perez, “SmartEnCity - Towards Smart Zero CO2 Cities across Europe,” 2015.

[44] U. Persson, “Quantifying the Excess Heat Available for District Heating in Europe,” Halmstad, 2015.

[45] H. Gadd and S. Werner, “Daily heat load variations in Swedish district heating systems,” *Appl. Energy*, vol. 106, pp. 47–55, 2013.

[46] L. F. Cabeza, Ed., *Advances in Thermal Energy Storage Systems*, 1st ed. Woodhead Publishing, 2015.

[47] “Marstal Fjernvarme.” .

[48] P. Eames, D. Loveday, V. Haines, and P. Romanos, “The Future Role of Thermal Energy Storage in the UK Energy System: An Assessment of the Technical Feasibility and Factors Influencing Adoption,” London, 2014.

[49] M. Karlsson, A. Gebremedhin, S. Klugman, D. Henning, and B. Moshfegh, “Regional energy system optimization – Potential for a regional heat market,” *Appl. Energy*, vol. 86, no. 4, pp. 441–451, 2009.

[50] J. N. Ferrer, “Using EU funding mechanism for Smart Cities,” 2013.

[51] J. Zeman and S. Werner, “District Heating System Ownership Guide.”

[52] D. Andrews, A. K. Riekkola, E. Tzimas, J. Serpa, J. Carlsson, N. Pardo-Garcia, and I. Papaioannou, “Background Report on EU-27 District Heating and Cooling Potentials, Barriers, Best Practice and Measures of Promotion,” 2012.

[53] A. P. Bertoldi, D. B. Cayuela, S. Monni, and R. P. De Raveschoot, *Existing Methodologies and Tools for the Development and Implementation of Sustainable*

Energy Action Plans (SEAP). European Commission, 2010.

[54] M. King and R. Shaw, “Community Energy: Planning, Development and Delivery,” 2009.

[55] D. Connolly, H. Lund, B. V Mathiesen, and M. Leahy, “A review of computer tools for analysing the integration of renewable energy into various energy systems,” *Appl. Energy*, vol. 87, no. 4, pp. 1059–1082, 2010.

[56] “energyPRO Software - Product Description.” [Online]. Available: http://www.emd.dk/.

[57] H. Lund, G. Šiupšinskas, and V. Martinaitis, “Implementation strategy for small CHP-plants in a competitive market: The case of Lithuania,” *Appl. Energy*, vol. 82, pp. 214–227, 2005.

[58] A. Fragaki and A. N. Andersen, “Conditions for aggregation of CHP plants in the UK electricity market and exploration of plant size,” *Appl. Energy*, vol. 88, no. 11, pp. 3930–3940, 2011.

[59] P. A. Østergaard, “Comparing electricity , heat and biogas storages’ impacts on renewable energy integration,” *Energy*, vol. 37, no. 1, pp. 255–262, 2012.

[60] A. Volkova, V. Mashatin, A. Hlebnikov, and A. Siirde, “Methodology for the Improvement of Large District Heating Networks,” pp. 39–45, 2012.

[61] “Termis User Guide.” [Online]. Available: http://www.schneider-electric.com/en/product-range/61418-termis-software/.

[62] A. Dalla Rosa and J. E. Christensen, “Low-energy district heating in energy-efficient building areas,” *Energy*, vol. 36, pp. 6890–6899, 2011.

[63] A. Dalla Rosa, R. Boulter, K. Church, and S. Svendsen, “District heating (DH) network design and operation toward a system-wide methodology for optimizing renewable energy solutions (SMORES) in Canada: A case study,” *Energy*, vol. 45, pp. 960–974, 2012.

[64] H. I. Tol and S. Svendsen, “Improving the dimensioning of piping networks and network layouts in low-energy district heating systems connected to low-energy buildings: A case study in Roskilde, Denmark,” *Energy*, vol. 38, no. 1, pp. 276–290, 2012.

[65] M. Brand, A. D. Rosa, and S. Svendsen, “Energy efficient and cost-effective in-house substations bypass for improving thermal and DHW (domestic hot water) comfort in

bathrooms in low-energy buildings supplied by low-temperature district heating," *Energy*, vol. 67, pp. 256–267, 2014.

[66] "NetSim User Manual." [Online]. Available: http://doc.energy.vitec.se/ManualData/ve/en/vitechelp.asp?produkt=NetSim&folder=netsim.

[67] L. Brand, A. Calvén, J. Englund, H. Landersjö, and P. Lauenburg, "Smart district heating networks – A simulation study of prosumers' impact on technical parameters in distribution networks," *Appl. Energy*, vol. 129, pp. 39–48, 2014.

[68] L. Brand and P. Lauenburg, "Prosumers in District Heating Networks - Problems and Possibilities," in *International Conference on Smart Energy Systems and 4th Generation District Heating*, 2015.

[69] L. Brange, J. Englund, and P. Lauenburg, "Prosumers in district heating networks - A Swedish case study," *Appl. Energy*, vol. 164, pp. 492–500, 2016.

[70] M. A. Ancona, M. Bianchi, L. Branchini, and F. Melino, "District heating network design and analysis," *Energy Procedia*, vol. 45, pp. 1225–1234, 2014.

[71] M. A. Ancona, L. Branchini, A. De Pascale, and F. Melino, "Smart District Heating: Distributed Generation Systems' Effects on the Network," *Energy Procedia*, vol. 75, pp. 1208–1213, 2015.