CHESTER

Compressed Heat Energy
Storage for Energy
from Renewable sources

D2.1 Case studies: User Requirements and Boundary Conditions Definition

PROJECT	**CHESTER**
PROJECT NO.	**764042**
DELIVERABLE NO.	**D2.1**
DOCUMENT VERSION	**V5.0**
DOCUMENT PREPARATION DATE	**15/10/2018**
RESPONSIBLE PARTNER	**PlanEnergi**
DISSEMINATION LEVEL	**Public**

Type of Deliverable		
R	Document, Report	**X**
DEM	Demonstrator, pilot, prototype	
DEC	Websites, patent fillings, videos, etc.	
OTHER		
ETHICS	Ethics requirements	
ORDP	Open Research Data Pilot	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 764042.

EC Grant Agreement	No.764042
Project Acronym	CHESTER
Project Title	Compressed Heat Energy Storage for Energy from Renewable sources
Programme	HORIZON 2020
Start Date of Project	01-04-2018
Duration	48 Months

Financial/Administrative Coordinator	
Project Coordinator Organization Name	TECNALIA
Address	Parque Tecnológico de Bizkaia C/Astondo, Edificio 700 (Spain)
Phone Numbers	+34 946 430 850
E-mail Address	eduardo.zabala@tecnalia.com
Project web-site	www.chester-project.eu

Version Management			
Filename	CHESTER D2.1 - Case Studies User Requirements and Boundary Conditions Definition		
Authors	Federico Bava, Dadi Sveinbjörnsson		
Reviewed by	Eduardo Zabala, Silvia Alonso		
Approved by	Eduardo Zabala		
Revision No.	**Date**	**Author**	**Modification description**
V0.1	25-06-2018	Eduardo Zabala	Move sections to annex
V0.2	26-06-2018	Federico Bava	Minor corrections
V0.3	26-06-2018	Silvia Alonso	Minor corrections
V0.4	27-06-2018	Carol Pascual	Add sections and comments
V1.0	28-06-2018	Federico Bava	Updates based on received comments
V1.1	29-06-2018	Eduardo Zabala	Last revision before delivery
V2.1	28-07-2018	Federico Bava	Added Turin case study
V3.1	25-08-2018	Federico Bava	Added Barcelona case study
V4.1	06-09-2018	Sven Stark, F. Bava, D. Sveinbjörnsson	Added Alpha Ventus case study
V4.2	05-10-2018	Carol Pascual	Ispaster minor changes
V4.3	12-10-2018	A. Carrera, F. Bava	Edition and revision of Barcelona case
V5.0	15-10-2018	Silvia Alonso	Final review

Contents

List of Figures

List of Tables

Glossary, Abbreviations and Acronyms

CAD	Computer-Aided Drawing
CHEST	Compressed Heat Energy STorage
CHP	Combined Heat and Power
DH	District Heating
DHC	District Heating and Cooling
DHW	Domestic How Water
DSO	Distribution System Operator
ETS	Emission Trading System
GHG	Greenhouse gas
HP	Heat Pump
HT	High Temperature
PCM	Phase Change Material
PSO	Public Service Obligations
PTES	Pit Thermal Energy Storage
PV	Photovoltaics
ORC	Organic Rankine Cycle
RES	Renewable Energy Sources
SCADA	Supervisory Control And Data Acquisition
TSO	Transmission System Operator
TES	Thermal Energy Storage
TTES	Tank Thermal Energy Storage
WtE	Waste to Energy

1. Introduction

1.1. Brief introduction to the CHEST concept

The main objective of the CHESTER project is the development and validation of an innovative system that allows for energy management, storage and dispatchable supply of many different RES, by combining the electricity and the heat sector. This is done by combining an innovative power-to-heat-to-power energy storage system, the so called CHEST (Compressed Heat Energy Storage) system with smart district heating, thus leading to a very flexible renewable energy management system, that is able to store electric energy with a very high round trip efficiency, site-independent (unlike pumped hydro), cyclically stable (unlike batteries), able to convert power into heat, able to convert low temperature heat into power, able to store and deliver independently from each other heat and power.

The CHEST system is based on existing technology (heat pump, HP; thermal storage, TES; Organic Rankine Cycle, ORC), but ground-breaking advancements are necessary to ensure high-efficiency and cost-competitiveness.

In the CHEST system, the HP consumes the surplus electricity from the grid to transfer heat from a low temperature heat source to a high temperature level (130-180°C), at which heat is stored in a high temperature thermal energy storage (HT-TES). The HT-TES is based on PCMs and needs to follow the temperatures of the heat transfer fluids of the HP (condenser) and the ORC (evaporator), so to lose as little exergy as possible.

When electricity is needed, the HT-TES can be discharged, working as heat source for an ORC cycle.

The principle scheme of a CHEST system, using the TES of a DH network as heat source for the HP and heat sink for the ORC, can be seen in Figure 1.

1.2. Purpose and Scope

This deliverable describes seven cases studies, which —despite very different boundary conditions— could benefit from the possible integration of a CHEST system. The case studies cover combinations of short- and long-term thermal energy storage, DH network at different temperature levels, access to excess heat, integration of different renewable energy sources (RES), different geographical location (Northern, Central and Southern Europe).

For each of these sites a technical report is elaborated, based on which it is possible to make a preliminary estimation of the potential benefit that the CHEST concept would bring to the existing systems.

Of the seven cases studies identified within the CHESTER project, as foreseen in the DoA, only six are presented in this deliverable:

- Turin (Italy): large DH network (>100 °C),
- Aalborg (Denmark): large DH network (<100 °C),
- Ispaster (Spain): small DH network and micro electrical grid,
- Barcelona (Spain): small DHC network,

- Alpha Ventus (Germany): offshore wind farm,
- Lekeitio (Spain): DH network (still in design phase).

The seventh case study of Strasbourg (France, large DH network) was not included in the deliverable, because at the time of writing (September 2018) a tender process prevented the disclosure of any type of information regarding this system. As the tender process is expected to last at least until the end of the 2018, it was decided to exclude the case study from the deliverable, to avoid delay in its submission.

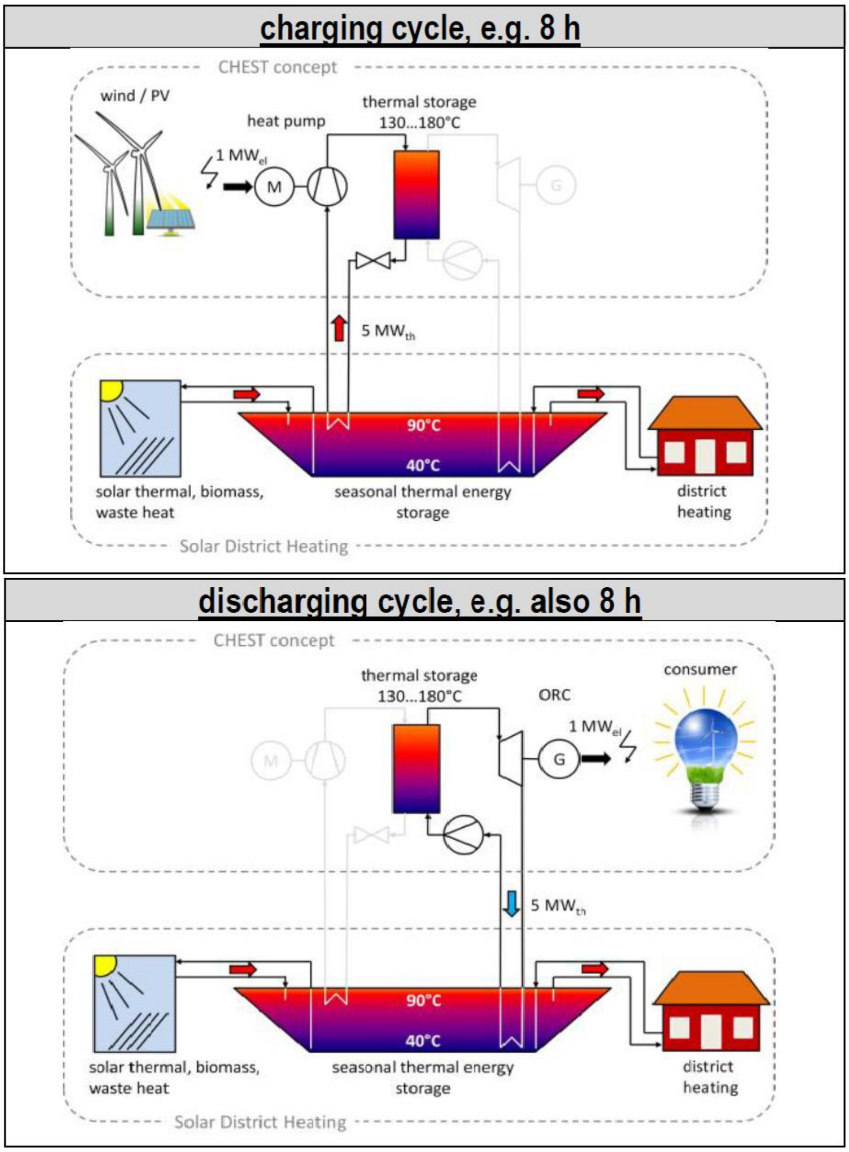

Figure 1: Principle scheme of a CHEST system integrated in DH system equipped with water pit storage.

1.3. Metodology

The information regarding the different case studies was collected by the relevant project partners from the utilities operating the installations. Two templates were sent out at this purpose. A first template required information regarding installed equipment, installed capacity, yearly productions and consumptions, control principles, relevant boundary conditions, etc. A more detailed overview of the requested information in this template is shown here below. Note that not all points are necessarily relevant for all the seven case studies.

- DH network
        - Length,
        - number of consumers.
    - Heat load:
        - yearly heat demand,
        - supply/return temperature,
        - expectations for future development.
    - Heat supply side. For each generation unit specify the following information
        - technology and fuel,
        - temperature levels,
        - yearly operational hours / energy output,
        - installed capacities,
        - priority of operation of the different units, regulation and control principles.
    - Thermal storage (info for both currently present and planned large PTES):
        - type (tanks/pit/others),
        - temperatures (if different than DH temperatures),
        - thermal losses,
        - volume,
        - charging/discharging control principles.
- Electricity production: For each generation unit specify the following information:
    - Technology,
    - installed capacity,
    - yearly electricity production,
    - electricity storage.
- Any other relevant information
    - local/national authorities position/plans for the energy system,
    - economic/technical/environmental constraints,
    - other.

A second template required 1-year data in the form 1-hour resolution time series for the following variables (note that not all points are necessarily relevant for all the seven case studies):

- timestamp (hourly or lower resolution),
- thermal power output for each heat generation unit and waste heat source,
- thermal power exchanged with the heat storage(s),
- electric power output from each electricity generation unit,
- heat load of the DH network,
- electric load of the municipality/region hosting the case study,
- spot electricity price for municipality/region,
- temperature levels of the DH system (if these are expected to have relevant variation on daily/seasonal basis),
- temperature levels of each heat generation unit and waste heat source (if these are expected to have relevant variation on daily/seasonal basis and different from the DH network temperature levels).

1.4. Structure of the document

This document is divided in six sections, one per each developed case study. The completed sections regard the case studies of Turin (Section 2.1), Aalborg (Section 2.2), Ispaster (Section 2.3), Barcelona (Section 2.4), Alpha Ventus (Section 2.5) and Lekeitio (Section 2.6).

Each section presents a general description of the case study, information on the heat and electricity demand, information on the generation units of both heat and electricity, existing boundary conditions (technical, legislative, environmental, economic) and the expected future development of these conditions and/or of the case study. Finally, a brief and qualitative potential assessment of the CHEST concept within the case study is presented.

The uncompleted case study of Strasbourg is listed in Section 3. A brief and general description is given, as presented in the Grant Agreement of the CHESTER project.

2. Case Studies

2.1. Case Study #1: Turin, Italy

Turin is a city and an important business and cultural center in northern Italy. It is the capital city of the Piedmont region, located in the North-West part of Italy. The population of the city itself is 883,281 people (as of 2017), while that of the urban area is estimated in 1.7 million inhabitants.

Most of the city is supplied by a DH network, which is managed by the multi-utility IREN SpA. In 2017, about 60 million m^3 of space heated volume were connected to the network, corresponding to approximately 600,000 inhabitants. The DH network is mainly fed with the heat produced by the modern combined-cycle plants operating in cogeneration mode.

Turin is currently in a leading position in the DH sector, having one of the largest networks in Europe [Jarre, 2016]. Due to the frequently polluted air —Turin ranks amongst the last positions in Europe for air-quality index—, local administrations have encouraged the development of DH, so to remove centralized residential boilers [Ravina, 2018]. Therefore, nowadays the residual individual heating systems are a minor source of pollutants in the urban environment. The Emission Inventory published by the Piedmont Region showed that road traffic was the main source of NO_x emissions (around 50 % of total). Energy production in the industrial sector and residential heating contributed for around 7 % and 5 %, respectively [Ravina, 2018].

The information presented in this section was made available by the company IREN, which is partner of the CHESTER Consortium. IREN is joint-stock multi-utility which operates in the sectors of production and distribution of electricity, district heating (where it is the largest Italian operator), water supply and water treatment.

2.1.1. Energy Demand

District Heating Demand

The main parameters of Turin's DH network are listed in Table 4, while a map showing the area currently supplied by the DH network is shown in Figure 6.

Table 1: Key figures on Turin's DH network. The values in the table refer to the year 2017.

Parameter	Value	Unit
Number of customers (substations)	6403	-
Network trench length	568	km
Yearly heat demand (2017)	2307	GWh
Supply temperature	120	°C
Return temperature	70	°C

The DH network is expected to expand in the coming years. Through an investment of about 280 M€ by 2021, the 60.3 million m^3 of space heated volume currently connected to the DH network are expected to increase by additional 13 million m^3 [IREN, 2017]. According to the municipal plans/agreements the areas of San Salvario, Northern Turin and the municipality of Beinasco in the southern outskirt of Turin will be connected to the DH network in the coming years [IREN, 2017].

DH consumption data for the year 2017 were made available in the form of time series with 5-minute resolution by IREN. The yearly heat demand of the DH network in 2017 reported in Table 1 is the measured at the plants' location, so it includes the thermal losses from the network, which can be estimated in 15-18 % of the yearly gross heat input to the network.

Electricity Demand

The yearly electricity consumption data are made available by TERNA, the Italian TSO, for each metropolitan city (administrative division). In 2015 and 2016 the yearly electricity consumption in the metropolitan city of Turin was 10.0 TWh [TERNA, 2018a]. Being that the metropolitan area of Turin has 2.27 million inhabitants, it can be estimated that the city of Turin alone (883,281 inhabitants) has a yearly electricity consumption of approximately 3.88 TWh.

An hourly load profile for each month of the year can be extrapolated from the national load profiles available on the TSO's website, where the requested power for each hour of the 3rd Wednesday of each month is reported [TERNA, 2018b].

2.1.2. Energy Supply

District Heating and Electricity Supply

Three CHP plants supply heat to Turin's DH network and electricity to the grid. The three CHP plants are Combined Cycle Gas Turbine (CCGT) plants, i.e. they make use of a gas turbine, whose hot flue gases power a steam power plant. Additionally, there are four groups of gas boilers, used as back-up and to cover peak loads. These boilers are steam generators gas boilers, having saturated steam/superheated water heat exchangers producing hot water for the DH network.

The different units supplying heat to the DH network and (when relevant) electricity to the grid are listed in Table 2, together with their nominal thermal and electric capacity and production in 2017 (for the gas boilers the heat production is given as cumulated thermal energy output, without distinction between the different units). The location of the listed plants in the urban area is shown in Figure 6. Detailed information on the CHP plants and boilers can be found online [IREN, 2018].

Table 2: Heat production units that feed into Turin's DH network.

Type of plant	Thermal power output (MW-th)	Thermal energy output (GWh-th/y)	Electric power output (MW-el)	Electricity production (GWh-el/y)
CCGT - North Turin	260	868	390	1919
CCGT - 2GT Repowering - Moncalieri	260	797	400	1849
CCGT - 3GT - Moncalieri	260	725	380	1739
Gas boiler - Moncalieri	141	136	-	-
Gas boiler - BIT	255		-	-
Gas boiler - Politecnico	255		-	-
Gas boiler - North Turin	340		-	-

The plant in Moncalieri is, together with the one in North Turin, the main source of heat that powers Turin's DH network. It consists of two CCGT plants, the 2GT and the 3GT plant, with a total electric power of 760 MW and a thermal power capacity in cogeneration of about 480 MW.

Each of the two plants in Moncalieri (2GT and 3GT) consists of [IREN, 2018]:

- a gas turbine (capacity of 270 and 260 MW-el for 2GT and 3GT respectively) with an efficiency of 39 %;
- a heat recovery steam generator, with three levels of pressure, supplied with hot (about 600 °C) flue gases from the gas turbine;
- condensing steam turbine (of 141 and 138 MW-el for 2GT and 3GT respectively), with regulated extraction of low-pressure steam to produce heat for DH;
- tube bundle condenser cooled by water from the Po river;
- heat production system for the DH network (260 MW-th) in the form of superheated water at 120 °C;

The overall electric efficiency of each of the two CCGTs is higher than 57 %, while in cogeneration mode the total efficiency of each plant is higher than 87 %.

Additionally, the plant is equipped with a 340 MW-th air-cooled heat dissipation system (at ambient temperature of 30 °C), usable from both 2GT and 3GT, if the cooling from the river water is not sufficient and/or when the electric power generation is profitable, which justifies the production of excess heat.

The plant in Moncalieri has also three steam generators gas boilers, having saturated steam/superheated water heat exchangers producing hot water for DH. The overall thermal power output is 141 MW-th [IREN, 2018].

Heat and electricity production data for the year 2017 from the different generation units, as well as energy transferred to/from the single TTESs, were made available in the form of time series with 5-minute resolution by IREN.

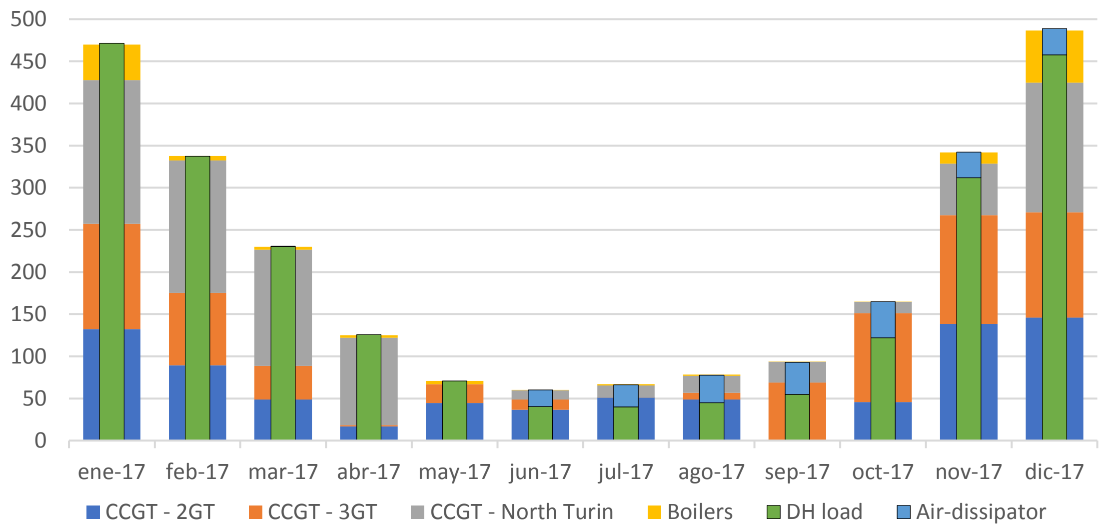

Figure 2: Monthly DH network load, thermal energy output from the different generation units in 2017.

Based on the data from 2017, the cumulated yearly heat production from the generation units listed in Table 2 was 2525 GWh, while the cumulated yearly electricity production from the CCGT plants was 5507 GWh. The monthly heat production from the different units listed in Table 2 as well as the DH load are shown in Figure 3.

The monthly electricity production from the cogeneration unit is shown in Figure 4. In the period between May and September, the shut-off of the different units one after the other corresponds to maintenance periods.

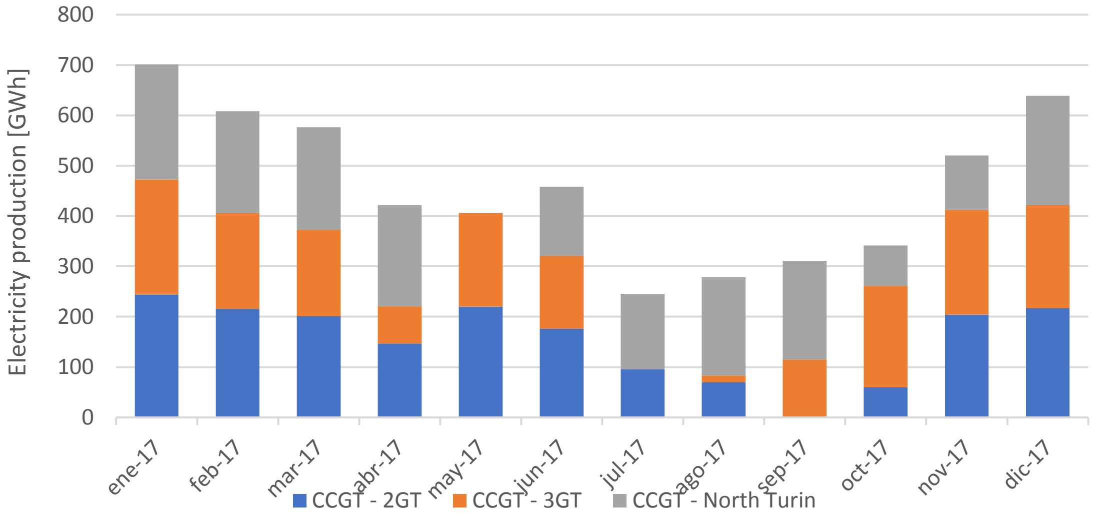

Figure 3: Monthly electricity production from the different CCGT units in 2017.

Following the extension of the Turin's DH network, the waste-to-energy (WtE) plant located in the area of Gerbido (southwest outskirts of the city) is planned to be connected to the DH network to feed-in heat starting from winter season 2019-2020 [La Voce, 2018]. In fact, the plant can operate in power-generation mode or in CHP mode. Put in operation in 2013, the plant currently burns 500,000 tons of municipal waste per year and produces around 300 GWh/year of electricity [TRM, 2018].

Energy Storage

A total volume of 15,000 m^3 of tank thermal energy storages (TTES) for pressurized hot water is installed to add flexibility to the system and to cover peak loads. The total storage volume is divided in four different systems as shown in Table 3.

Table 3: TTES and storage volumes connected to Turin's DH network [IREN, 2018].

TTES system/ Location	Number of tanks	Volume (m^3)
North Turin	6	5000
Martinetto	6	5000
BIT	6	2500
Politecnico	4	2500

In the winter season the TTES are normally charged during night and discharged during morning peaks of demand. They are also discharged, when high electricity market prices or ancillary services give an incentive to the CHP plant to operate in power-generation mode. The use of the

TTES to cover peak demands in the early mornings of the winter seasons can be appreciated in Figure 4. In both Figure 4 and Figure 5 the thermal power exchanged with the TTES is positive when the TTES is discharged and negative when the TTES is charged.

In Figure 5 for 10th July 2017 (on this day the units CCGT - 2GT, CCGT - 3GT and the boilers were off).

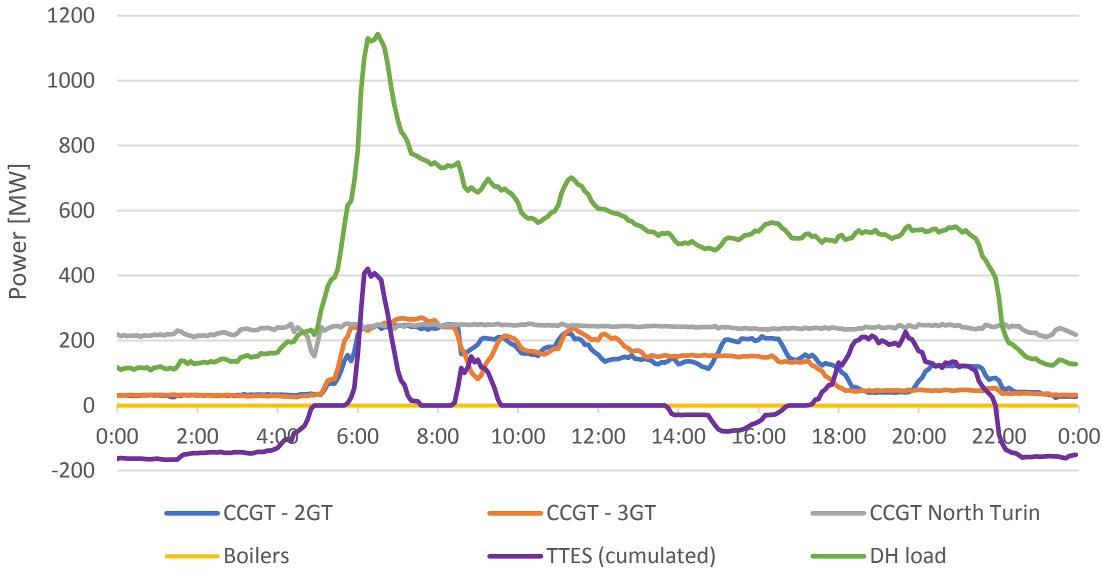

Figure 4: DH network load, thermal power output from the different generation units and thermal power exchanged with the TTESs on 22nd February 2017.

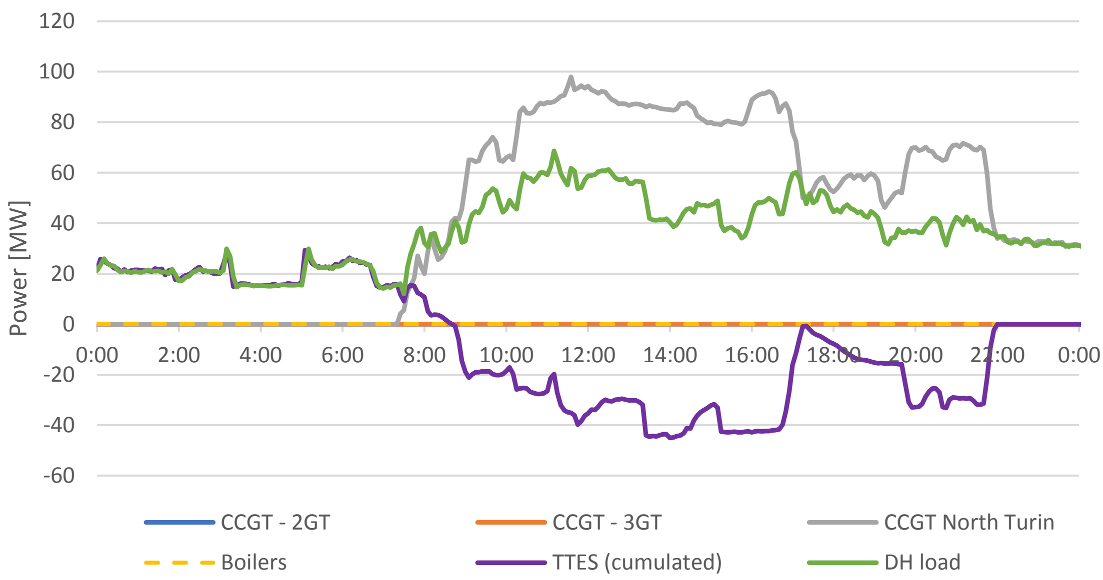

Figure 5: DH network load, thermal power output from the different generation units and thermal power exchanged with the TTESs on 10th July 2017.

2.1.3. Existing Boundary Conditions

With the Legislative Decree 4 July 2014 no. 102, the European Directive 2012/27/EU for the promotion of energy efficiency was incorporated into the national legislation. According to this decree, the Authority for Energy started regulating the DH sector.

The DH sector is also subject to accounting unbundling, so to make the sector more transparent and homogeneous, allow the verification of the costs of the service and to ensure their correct disaggregation and attribution, by promoting competition and efficiency, as well as adequate levels of quality in services.

Due to the lack of information in this case study regarding the existing boundary conditions a more detailed analysis has not been able. Nevertheless, a detailed analysis of the political, economic, social, technological, environmental and legal boundary conditions of the Italian energy sector in general and of the electricity sector in particular is presented in the deliverable D6.1 of the CHESTER project.

2.1.4. Future Perspective

Italy has implemented several policy measures to reach its 2020 targets regarding energy efficiency, RES and GHG emissions. Many objectives have already been met due to the impact of the economic crisis on the country. However, it should be determined whether an economic turnaround would compromise Italy's ability to reach its targets. According to the National Energy Strategy, Italy should take a leadership role in the adoption of the European 2050 Energy Roadmap and should aim at reducing CO_2 emissions by 80-95 % in 2050 with respect to the 1990 level.

The National Energy Strategy does not specify objectives at for the single sectors or technologies, but it is technology-neutral and flexible to changes in the market conditions. Additionally, the National Energy Strategy regards DH as an example of optimal use of local resources, integrating RES, waste heat and efficient CHP plant.

2.1.5. Potential of the CHEST System

The results from the analysis of the boundary conditions and the future perspective for this case study were not satisfactory enough. Therefore, due to this lack of information, the conclusions about the potential of a CHEST system for this case study would lack the necessary technical rigour and have not been worked out.

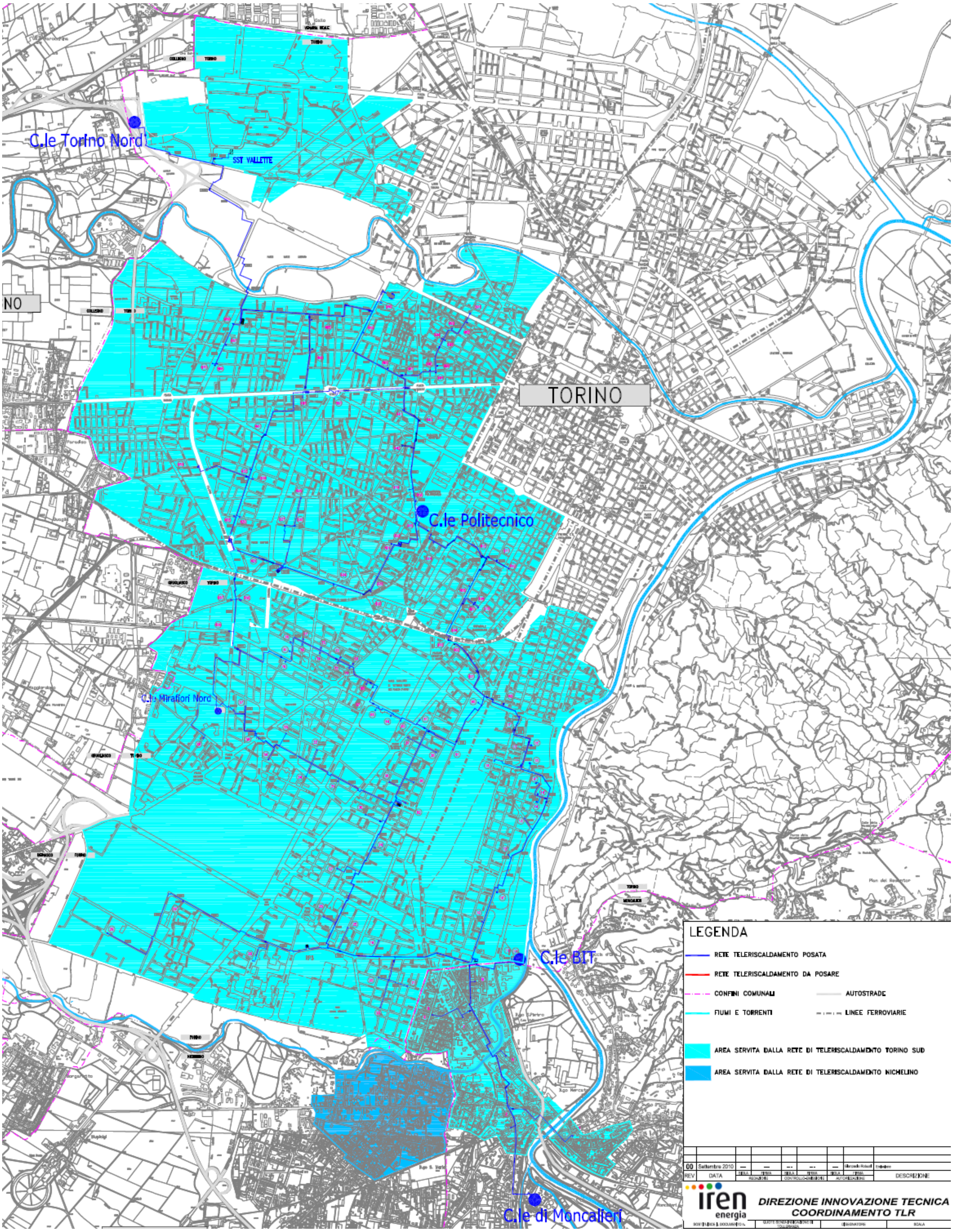

Figure 6: Area supplied by Turin's DH network and heat generation plants (Figure by IREN).

2.2. Case Study #2: Aalborg, Denmark

Aalborg is located in the Northern part of the Jutland Peninsula in Denmark. It is Denmark's 4th largest city with a population of 114,000 (as of 2018). Most of the city is supplied by a DH network, which is managed by the municipally-owned utility company Aalborg Forsyning. In 2016, 98 % of heated buildings within the area covered by the DH network were connected to the network, for a total number of 36,716 customers. Multiple-apartment buildings are counted as a single customer, so the number of households supplied by the DH network is higher than the number of customers. Most of the heat demand occurs in the period October-May, as there is much less space heating demand between May and September.

A large cement producer, Aalborg Portland, is located just outside the city and supplies the DH network with large amounts of industrial excess heat. There are plans of building a large long-term pit thermal energy storage (PTES), so that the excess heat which is not required in summer can be stored and used later in winter. Additionally, Aalborg has a waste incineration combined heat and power (CHP) plant and a large coal-fired CHP power plant, both of which supply heat to the DH network and electricity to the electrical grid.

2.2.1. Energy Demand

District Heating Demand

Some key parameters of Aalborg's DH network are shown in Table 4. The DH network is expected to expand in the coming years, with an increase in the heat demand of about 2,500 MWh/year in the period 2017-2021, primarily due to new buildings. Afterwards, a reduction in heat demand by approximately 0.2 % per year is expected.

DH consumption data were made available in the form of time series in 1-hour resolution by the manager of the DH network.

Table 4: Key figures of the Aalborg's DH network. Values refer to 2016 [Aalborg Varme, 2016].

Parameter	Value	Unit
Number of customers	36,716	-
Transmission pipelines, length	91.9	km
Distribution pipelines, length	851.5	km
Consumer's lines, length	648.7	km
Total DH network length	1592	km
Yearly heat demand (gross)	1972	GWh
Supply temperature (distribution)	90	°C
Return temperature, summer	50	°C
Return temperature, winter	40-45	°C

Electricity Demand

The municipality of Aalborg, which includes the city of Aalborg and a number of smaller towns in the area, has a population of 214,000 (as of 2018). The yearly electricity consumption in the municipality was 1339 GWh in 2015 and 1398 GWh I 2016. Historical electricity load profiles and market spot prices for the electric grid of West Denmark (DK-West or DK1) are available online in the form of time series in 1-hour resolution [Energi Data Service, 2018]. Assuming that the electricity demand of Aalborg follows a similar profile to that of DK1 region, the yearly consumption of the municipality can be distributed over the year, so to obtain a coherent 1-hour timestep demand profile.

2.2.2. Energy Supply

District Heating and Electricity Supply

There are three CHP plants and various thermal energy generation units and excess heat sources that supply heat to Aalborg's DH network and electricity to the grid. The DH producers are listed in Table 5. The different DH producers are shown in terms of production capacity, yearly energy output and operation priority (from 1 to 9 with decreasing priority).

Table 5: Heat production facilities that feed into the Aalborg DH network [Aalborg Forsyning, 2015].

Priority	Heat producer	Type	Thermal energy output (GWh/y)	Max. power, average over 10 minutes (MW-th)	Max. power, average over 24 hours (MW-th)
1	Reno-Nord	Waste incineration CHP	448	47 (summer) 60 (winter)	42 (summer) 45 (winter)
2	Various small sources	Excess heat	1	5	
3	Aalborg Portland cement factory	Excess heat from flue gas	239	70	70
4	Waste water treatment	Biogas CHP	3	1.65	1.65
5	Aalborg Portland cement factory	Excess heat from flue gas, II	99	32	32
6	Reno-Nord	Waste incineration, II	-	18	18
7	Nordjyllandsværket	Coal CHP & electric boiler	1070	465	465
8	Peak load & redundancy plants	Natural gas	68	300	300
9	Peak load & redundancy plants	Oil	-	200	200

The DH producers in Table 5 are ordered based on the operation priority of the heat generation facilities. This prioritization is politically determined by Aalborg's city council, with the aim of maximizing the utilization of industrial excess heat and waste incineration and minimizing the utilization of fossil fuels for heat generation. The waste incineration plant has the highest priority (base load operation), so to secure the incineration of the municipal waste received by the plant (up to 45 MW). The industrial excess heat from the flue gas of Aalborg Portland cement factory also has a high priority (up to 70 MW), as this heat would otherwise be wasted. Two waste water treatment plants in Aalborg produce biogas via anaerobic digestion, which is used for heat and electricity production in a small biogas CHP plant, which has a high operation priority. Additional heat production from Aalborg Portland (up to 32 MW) and from waste incineration (up to 18 MW) is possible, if needed.

Aalborg has a coal-fired CHP plant (called Nordjyllandsværket), which is operated at middle-high loads in winter. This plant is operated to obtain the lowest total heat production costs, which sometimes results in operation that is focused on producing electricity, when the electricity spot prices are high. In fact, a high revenue from electricity sales makes it possible for the plant to sell heat to the DH network at lower prices. The DH network finally has a number of natural gas and oil-fired boilers, which are only used for peak loads (if needed) or during outages of other heat producers.

The electricity generation units are listed in Table 6.

Table 6: CHP plants connected to Aalborg's DH network.

Electricity producer	Type	Max. power (MW-el)
Reno-Nord	Waste incineration CHP	15
Reno-Nord, II	Waste incineration CHP	5.5
Nordjyllandsværket	Coal CHP	410
Nordjyllandsværket	Diesel turbine	24
Waste water treatment	Biogas CHP	-

Energy Storage

The thermal energy storage capacity connected to the DH network is shown in Table 7. There are two steel tank storages (TTES) in operation. The larger TTES is a buffer tank situated at the coal-fired CHP plant. The tank gives some flexibility to the CHP plant with respect to heat generation and allows it to operate based on the electricity spot prices, when this is feasible. The smaller TTES is a buffer tank situated in the downtown area for balancing demand peaks (for up to 2.5 days).

Table 7: Key figures for the existing and planned TES in Aalborg's DH network.

Type of storage	Max. Temperature (°C)	Min. Temperature (°C)	Volume (m^3)	Status
TTES	90	50	24,000	In operation
TTES	90	50	22,000	In operation
PTES	80	40	2 x 500,000	Planned

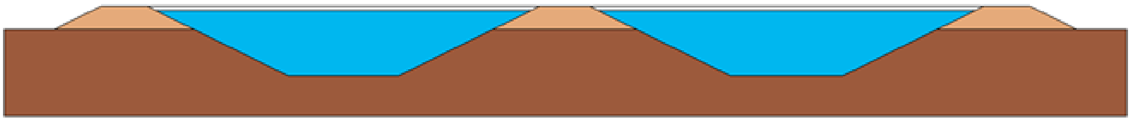

Figure 7: A schematic representation of the cross-section of the planned PTES (Figure by PlanEnergi).

In addition to the existing TTES, a 1,000,000 m^3 pit thermal energy storage (PTES) is being planned. The purpose of the PTES would be to store the industrial excess heat produced in summer, which is not recovered today, due to low heat demand in this season. The PTES would most likely be realized as two 500,000 m^3 pits next to each other, sharing one of the side walls. This has some advantages for the stratification (temperature layering) in the storage and for the technical lifetime of the lid materials. The area required for the two PTESs is approximately 11 hectares. A schematic visualization of a cross-section of the double PTES is shown in Figure 7.

The side walls are dimensioned for soil-balance, i.e. so that the excavated soil is used for the formation of the side walls (no soil must be delivered or disposed of during the construction of the PTES). The white lines on the water surface represent the lid of the storages, which is insulated and floats on the water.

2.2.3. Existing Boundary Conditions

District Heating

There are around 400 DH networks in Denmark and 63 % of all private houses are connected to DH for both space heating and domestic hot water supply [DEA, 2017]. DH in Denmark is regulated under the heating supply law by the national government. According to the law, municipalities are responsible for carrying out heat planning within the municipality and approving heating projects. The DH companies that own and run the DH networks and heat generation units are also frequently owned by the municipality itself. In areas with DH, municipalities can impose an obligation to connect and to remain connected to the DH network.

Before a DH project (new installation or major modification of a DH unit or network) can be carried out, a project proposal that documents socio-economic, user-economic, financial and environmental feasibility (compared to different project alternatives) must be prepared. The proposal must be prepared based on the assumptions and guidelines of the Danish Energy Agency. Additionally, DH supply in Denmark is subject to rules and regulations that ensure that DH companies are operated on a non-profit basis. This is because DH is a natural monopoly, and through the non-profit principle, the DH customers are protected from an otherwise possible abuse of this monopolistic setup.

Fossil fuels for heat generation are subject to an energy tax. Biomass for heat generation is not taxed, which gives Danish DH companies an incentive to use biomass rather than fossil fuels. Industrial excess heat that is used for heating is also taxed. The industrial excess heat tax is effectively payed by the company that generates the heat. However, a company selling industrial excess heat to a DH network would likely require a reimbursement for this tax from the DH company. Additionally, fossil fuels and biomass are subject to taxes related to the emissions arising from their combustion. The taxation on fuels and excess heat for DH purposes is shown in Table 8.

Table 8: Taxation on fuel for heat generation. Energy tax values refer to 2018; CO_2, NO_x and SO_2-tax values to 2016.

Energy source	Units	Energy tax	CO_2 tax	NO_x tax	SO_2 tax	Total
Heating oil	€/GJ	7.45	1.70	0.17	0	9.32
Natural gas	€/GJ	7.45	1.30	0.13	0	8.88
Coal	€/GJ	7.45	2.17	0.35	0.31	9.97
Biomass	€/GJ	0	0	0.32	0.24	0.56
Industrial excess heat	€/GJ	6.85	0	0	0	6.85

Electricity

The Danish electricity transmission system is split up in two zones, DK-West and DK-East. Aalborg is located in the DK-West (also called DK1) zone. Interconnectors connect the DK-West zone to the DK-East zone as well as to Germany, Norway and Sweden. A further interconnection to the Netherlands is being implemented, and another to England is undergoing a feasibility study.

There is a large number of onshore and offshore wind turbines in the DK-West area, and 42 % of Denmark's electricity demand was supplied by wind power in 2016. This gives rise to fluctuating electricity spot prices and a need for electricity producers able to regulate the electricity production and the frequency in the electricity network on short time scales. The Danish TSO purchases these ancillary grid services as needed from those that can provide them (e.g. dispatchable power plants) at a higher price than the electricity spot market price.

Wholesale prices in Denmark tend to be higher than in the rest of the Nordic region, but lower than in the rest of Europe. This is mainly because Denmark lies between Norway (with its relatively inexpensive hydro) and the rest of Europe (with more expensive thermal generation).

Electricity consumption is subject to an energy tax and tariffs on top of the spot price. These are shown in Table 9. The taxation varies depending on the electricity use. Electricity used for heating purposes, both in electric heating, small heat pumps and for large installations in DH networks, is taxed considerably lower than other general electricity consumption. Electricity consumption for industry is almost exempt from the energy tax. All electricity consumption (regardless of type) is subject to paying transmission and system tariffs to the TSO. Electricity customers that connect directly to the transmission system (132/150 kV) are exempt from the system tariff and pay only 4.83 €/MWh to the TSO. All electricity consumption is also subject to the Public Service Obligations (PSO) levy. The PSO is, however, currently being phased out and will be abolished by 2022. CO_2, NO_x and SO_2 taxation is not charged directly on electricity, but will indirectly affect the electricity price, if electricity is produced based on a fuel affected by the taxes (see Table 8).

Table 9: Tax rates for electricity depending on what it is used for. Energy tax, transmission and system tariff and PSO values for 2018.

Energy source	Unit	Energy tax	Transmission & system tariff (to TSO)	PSO	Total
Electricity (for heating)	€/MWh	36.90	10.74	19.73	67.37
Electricity (for industry)	€/MWh	0.54	10.74	19.73	31.01
Electricity (for other uses)	€/MWh	122.70	10.74	19.73	153.17

A more detailed analysis of the political, economic, social, technological, environmental and legal boundary conditions of the Danish energy sector in general and of the electricity sector in particular is presented in the deliverable D6.1 of the CHESTER project.

2.2.4. Future Perspective

Denmark has long-term targets regarding the reduction of greenhouse gas (GHG) emissions. Denmark aims at covering half of its energy demand with RES by 2030. Denmark used to have an official goal of being independent from fossil fuels by 2050, but this target has now been abandoned by the current government. Denmark also has some international commitments under UN and EU regulations. These include [IEA, 2017]:

- A reduction of non-ETS greenhouse gas emissions by 20 % in 2020 compared to 2005 (the goal is projected to be reached with current policy).
- An increase in the share of RES in the gross finale energy consumption to 30 % by 2020 (the goal is projected to be reached with current policy).

- An increase in the share of RES in land-based transport to at least 10 % by 2020 (the goal is not projected to be reached with current policy).

Given these targets and commitments, future changes in energy taxes, tariffs and incentives are expected to help move the country further away from fossil fuels and more towards sustainable energy sources. Hence, taxes on fossil fuels are unlikely to be lowered. On the other hand, the energy tax on electricity for heating purposes has recently been lowered by 25 %, and a further lowering is being discussed.

An increased share of energy from RES, i.e. wind power, PV and solar thermal, play a key role in reaching the above-mentioned targets. An increased share of fluctuating energy sources is likely to induce a need for more sector coupling (e.g. power-to-heat via heat pumps) and for more energy storage solutions (e.g. thermal energy storages and hybrid energy storages such as the CHEST system). Incentives towards increased energy efficiency are also expected to play a key role in reaching the climate targets.

The role of DH in the Danish heating sector is not expected to decrease in the future. The DH supply is expected to move increasingly away from fossil fuel usage and towards biomass (in the short and medium term) and electrification through large-scale heat pumps (starting now and increasingly in the medium and long term).

2.2.5. Potential of the CHEST System

From an energy system point of view, the integration of a CHEST system in the electrical grid and DH system of Aalborg could be very interesting. The “user” and possibly the operator and/or owner of the CHEST system could be the same DH company Aalborg Forsyning.

The CHEST system could utilize the planned PTES (and the excess heat available) as a low-temperature (<100 °C) thermal energy storage. On the other hand, a high-temperature (>100 °C) thermal energy storage, a high-temperature HP and an ORC —as well as the necessary connections to the PTES and to the electrical grid— should be installed. The CHEST system could draw heat at approximately 60-90 °C (depending on the time of year) from the PTES during HP operation and return heat at approximately 10-40 °C during ORC operation. When in HP operation mode, the CHEST system could exploit fluctuating electricity supply from wind turbines, which is large in the DK-West area. So, the CHEST system would also help balance the electrical grid. A principle scheme (both HP and ORC operation) of how the CHEST system could be integrated in Aalborg’s energy system is given by Figure 1. The source of low-temperature heat (bottom-left corner of the two principles scheme in Figure 1) can be excess heat and/or heat from waste incineration (Table 5), which are available regardless of the seasons, i.e. of the heat demand from the DH network.

Technically, the system could likely be integrated very well in Aalborg’s energy system. It is also likely that the CHEST system would enable the integration of more electricity from renewable sources in the DK-West electrical grid.

The large size of Aalborg’s DH system and the planned PTES would allow the integration of a relatively large CHEST system, which would likely give a better economic feasibility compared to a small system thanks to the economies of scale.

The investment costs, and operation and maintenance costs and possible taxation of the CHEST system would need to be covered by the difference in the electricity spot prices when charging (HP operation) and discharging (ORC operation) and by possible payments from the TSO for any auxiliary grid services (primary reserves, frequency stabilization) that the CHEST system can offer. It is not clear beforehand to which extent it would be private-economically or socio-economically feasible to integrate the CHEST system in the energy system of Aalborg. This should be analyzed in other parts of the CHESTER project.

2.3. Case Study #3: Ispaster, Spain

Ispaster is a small town of 706 inhabitants (as of 2017), located in the Basque Country (Spain), 49 km northeast from Bilbao.

An electrical micro-grid (besides the local DSO grid) and a small DH network were recently implemented in the town, to supply sustainable energy based on local renewable sources to the public buildings of the town. Local renewable energy comes in form of heat, produced by a biomass boiler and solar thermal collectors, and electricity, produced by PV panels and possibly stored in electric batteries. That in Ispaster does not represent a large installation, but it may provide interesting boundary conditions for analyzing the potential of a CHEST system integrated into an energy system with a high share of RES.

Besides the peculiar technical boundary conditions, the case is also interesting for the business model that has been applied, characterized by public-private collaboration in a long-term approach, creation of a cooperative with local based companies (EZE Barrizar), high commitment of public authorities and active involvement of citizens.

The information presented in this section was made available by the company EZE Barrizar [EZE Barrizar, 2017a].

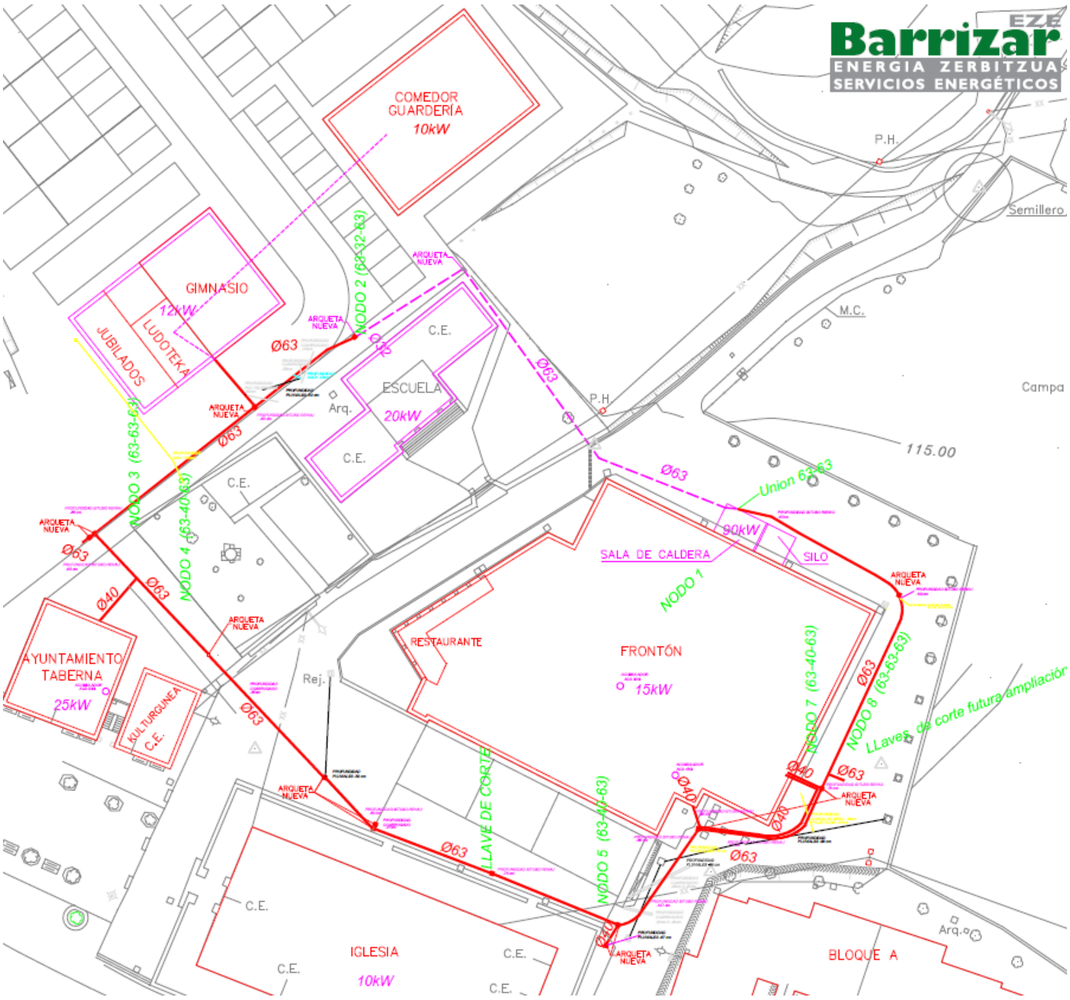

Figure 8: CAD representation of the DH network. The DH ring is represented by the thick red lines and by the dashed pink lines.

2.3.1. Energy Demand

District Heating Demand

A small DH network (in a shape of a ring, see Figure 8) was installed between 2014 and 2015, to supply heat to 11 public buildings. These were the local school (*Escuela* in Figure 8), city hall (*Ayuntamiento*), bar (*Taberna*), pelota court (*Fronton*), restaurant (*Restaurante*), kindergarten (*Guarderia*), canteen (*Comedor*), retirement home (*Jubilados*), gym (*Gimnasio*), play center (*Ludoteka*) and cultural center (*Kulturgunea*). In 2015, only the school was connected to the DH ring, while all the other buildings except the cultural center were connected between November 2015 and January 2016. Finally, the cultural center was added in May 2017.

Simultaneously different measures to improve the energy efficiency and reduce the heat demand of the buildings were adopted. These included the installation of heat recovery ventilation, mixed Venturi-forced ventilation, replacement of inefficient carpentry and use of double-panes glass with low emissivity.

The network has a trench length of 800 m and is made of pre-insulated pipes of cross-linked polyethylene, with the largest pipe diameter being 63 mm. The supply and return temperature are 75 °C and 55 °C respectively. The water content of the network is 1000 l, while on the load side there are 6 DHW tanks for a cumulated volume of 1000 l, which contributes to the thermal inertia of the system. In 2017 the yearly heat demand from the connected consumers was 65 MWh, while in the 12-month period April 2017-March 2018 (when also the cultural center was connected) it was 66 MWh. The month-by-month distribution of the heat demand in this period is shown in Figure 9.

Of the 11 buildings the kindergarten and the gym have an additional thermal energy source in the form of gas boilers. Although their use during the year is very limited, they are turned on in case of high heat demand of the corresponding buildings, in order not to destabilize the DH ring.

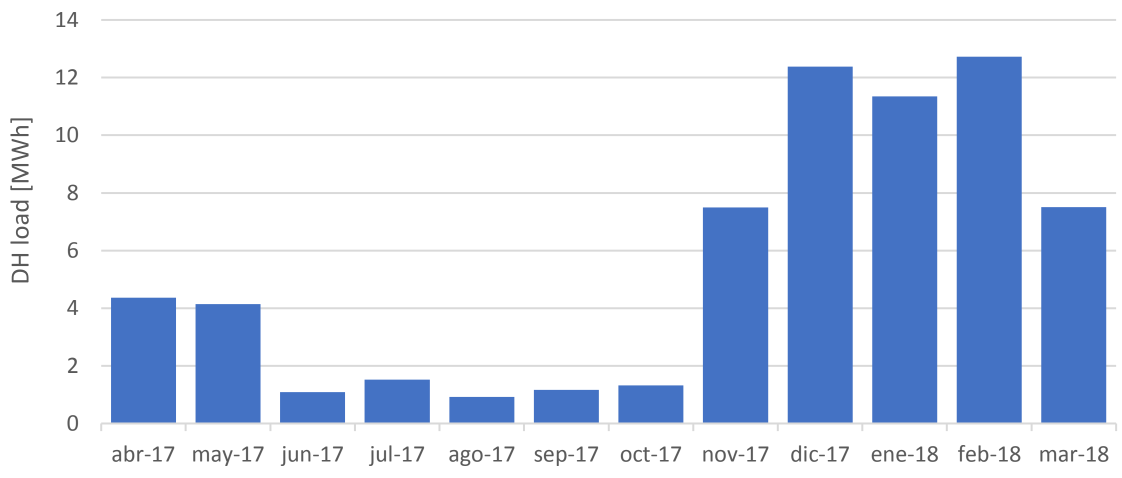

Figure 9: Monthly load of the DH network in the period April 2017-March 2018.

Electricity Demand

Regarding the current situation (spring 2018) of the electricity supply of the buildings connected to the DH ring, we distinguish between:

- buildings connected to the DSO grid only: school, bar and restaurant;

- buildings connected to the electrical micro-grid only: kindergarten & canteen, gym & retirement home & play center, and the boiler room of supplying the DH network (*Sala de Caldera* in Figure 8);
- buildings connected both to the DSO grid and to the micro-grid for the actual supply: pelota court, city hall, cultural center.
  Despite the connection to the DSO network of the city hall and the cultural center, the actual purchase of electricity is minimal, thanks to the micro-grid (see Section 2.3.2). However, the connection of the buildings to the DSO network must be maintained for legislative reasons.

The presence of the micro-grid allowed canceling two electricity supply contracts with the DSO (retirement home + play center + gym and kindergarten + canteen), with significant economic savings. In fact, the cost structure of the electricity bill in Spain is characterized by a large share (more than 50 %) of fixed cost. Hence, a customer would receive a fairly expensive electricity bill, even when consuming very little electricity.

The sum of the peak powers of the buildings connected to the micro-grid is 48 kW. Currently there are not precise data available on the yearly electricity demand of the buildings connected to the micro-grid, but this is estimated in approximately 27 MWh.

2.3.2. Energy Supply

District Heating Supply

A principle scheme of the DH network is shown in Figure 10. The DH network is fed mainly by a 90 kW wood chips boiler with a nominal efficiency of 92 %, located in a technical room next to the pelota court (*Sala de Caldera* in Figure 8). The wood chips fed to the boiler derive from biomass collected in the forests around Ispaster. With a lower calorific value of 12-16 MJ/kg (at humidity content <20 %), the availability of 35,000 tons/year of biomass from the surrounding forests is more than enough to meet the local heat demand.

The water at the outlet of the boiler has a temperature of 80 °C and is pumped into a buffer tank of 5000 l, which avoids an intermittent on/off operation of the boiler. Additional 2000 l of tank storage are installed in the basement of the play center (*Storage tank* in Figure 10). The tank was not connected yet at the time of writing (September 2018), but it is expected to be connected by the end of the year, if the new budget is approved. The purpose of this tank is to reduce the response time from the DH network, when there is a high heat demand from the buildings of the so-called *B Block* in Figure 10. The *B Block* consists of the retirement home, the gym, the play center, the canteen and the kindergarten. Additionally, the storage tank ensures the designed comfort temperature without increasing the total power of the boiler.

Another heat source for the DH ring is represented by vacuum tube + CPC solar collectors, which were installed on the roof of the pelota court in November 2016, south-west oriented. Water is used as solar collector fluid so, if too low temperatures occur in winter, the circulation pump is activated to avoid freezing. The collectors have a gross area of 59 m^2 (useful area of 54 m^2), which correspond to an installed capacity of 41.5 kW. The solar collector system is equipped with a 2000 l buffer tank.

Assuming typical weather condition for Ispaster area, the yearly energy output from the solar installation would be about 34 MWh. Data on the actual energy output from the collectors are not currently available, but this is likely to be lower than the theoretical output of 34 MWh/year, given the low heat demand in the summer period, when the collectors produce the most. The installation of a SCADA system for monitoring is planned for 2018, so more detailed data will soon be available.

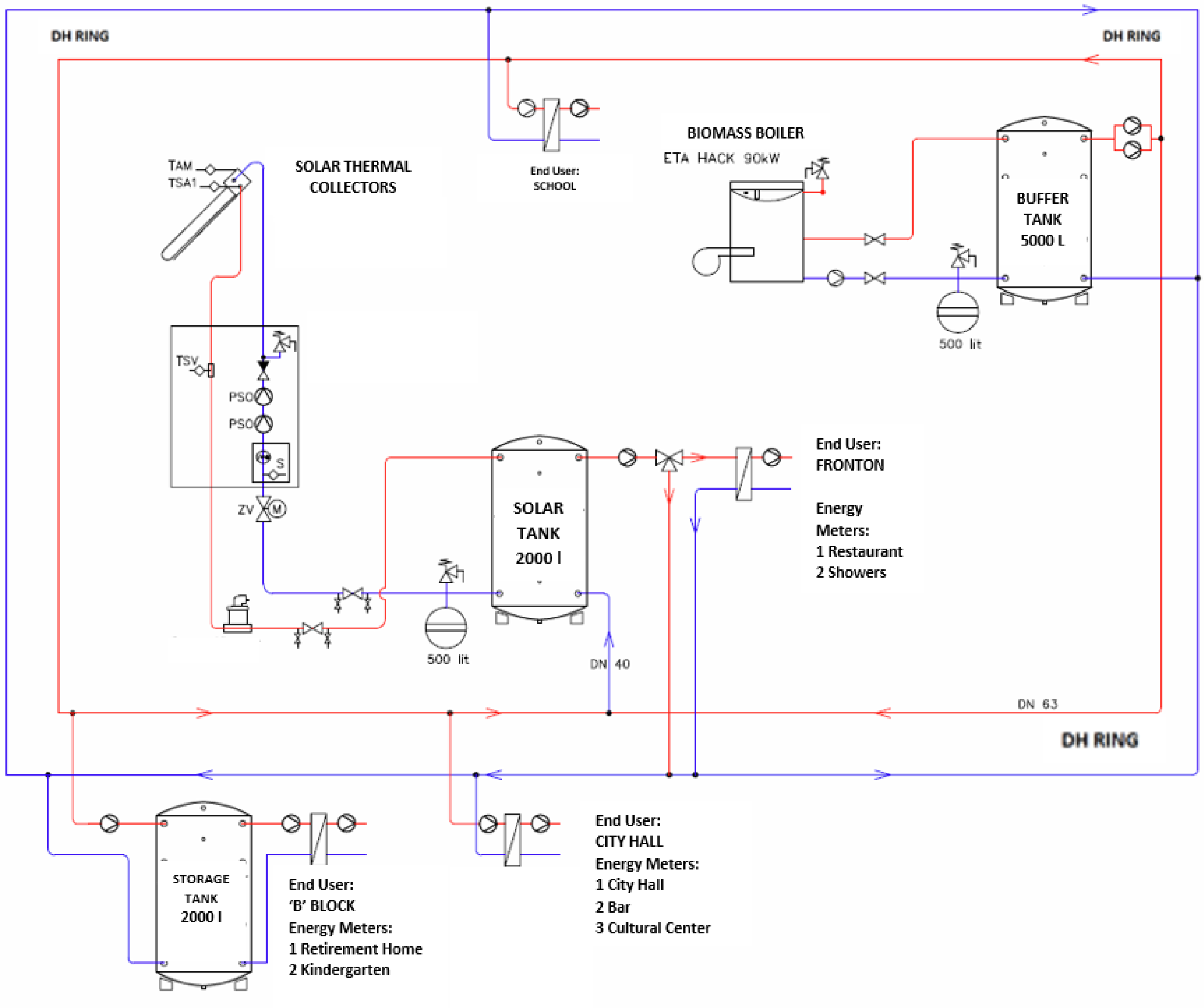

Figure 10: Principle scheme of DH network in Ispaster, supply and demand side.

The overall yearly energy output from both boiler and solar thermal collectors in 2017 was 112 MWh, which —compared to a yearly heat demand of 65 MWh— entails an efficiency of the system of approximately 60 %.

Electricity Supply

In 2017, 100 PV panels were installed on the roof of the pelota court, south-west oriented. The total capacity of the array is 25 kW and the nominal efficiency of each module is 16.1 %. When the PV power output is higher than the demand, the excess electricity is stored in lead-acid batteries (48 V / 4100 Ah) for an overall gross capacity of 197 kWh (138 kWh net). This corresponds to two days of self-sufficiency.

Nine inverters of 5.5 kW each (peak efficiency 95.8 %) almost perfectly match the expected peak power demand of 48 kW (see Section 2.3.1).

Assuming typical solar radiation conditions for Ispaster area, the yearly electricity production from the PV installation would be around 21 MWh (in case of no curtailment). However, the present electricity production is much lower (estimate of about 14 MWh/year), because the excess PV electricity produced cannot be sold to the electrical network for legislative reasons. Hence, when the batteries are fully charged, and the PV panels produce more electricity than required, the excess electricity is curtailed.

2.3.3. Existing Boundary Conditions

It should be pointed out that Ispaster —with its high share of RES, especially for electricity production— represents somehow an exception in the Basque Country, where most of the primary energy comes from fossil fuels and a good portion of the used electricity is imported. For a wider perspective on the existing boundary conditions of the energy sector in the Basque region, the reader may refer to Section 2.6.3 (Lekeitio case).

From a national perspective, the thermal related activities, such as distribution of heat through a DH network, do not have any type of political/legal barriers in Spain. The electricity sector, however, is quite different. Below are summarized the main points characterizing the present scenario.

In Spain there have been different plans to boost the penetration of RES for electricity production. Especially PV boomed between 2007 and 2008, with installed capacity increasing from 637 MW to 3,355 MW. However, this unexpected boom had dramatic consequences, such as a large and growing “tariff deficit”, which appeared soon unsustainable. So, in the wake of the 2008 financial crisis, the Spanish government drastically reduced subsidies for PV. Shortly after support for new installations was totally removed and even the previously offered feed-in tariff for already installed PV systems were strongly reduced. This caused many international lawsuits and, in general, a large uncertainty about new proposals.

The current regulation (Law 24/2013 and 900/2015) identifies two types of PV installations. The first type includes installations connected to the grid and with a capacity lower than 100 kW. Any excess electricity which is fed into the grid is not rewarded. The second type includes larger installations, which can sell the surplus electricity on the market as any other producer, paying the grid-access charge and the generation tax. Both types of installations are charged for the self-consumed electricity through the so-called sun tax (installations below 10 kW are exempted) [López Prol, 2017].

The recent years have been slightly brighter for renewable electricity sources. Their investment cost has reduced significantly. Realizing that the 20-20-20 targets could not be reached, the Government approved new schemes, but trying to limit the profitability. Two large auctions for renewable energy capacity to be constructed by 2020 took place in 2017: PV and wind projects were assigned 4 GW each. The current market conditions (Spain has one of the highest electricity prices in Europe before taxation [Eurostat, 2018]) made these installations seem interesting, even without a fixed subsidy. In fact, the previously feed-in tariff system for renewables was replaced by a regulated asset-based system. With this system, an installation was recognized an asset value, remunerated by the government to ensure a "reasonable rate of return" (RRR). This mechanism implied that the government would provide subsidies, only if the pool electricity prices were not high enough to reach the RRR. In the auctions, all the bids were awarded at the maximum discount rate allowed, so that it is unlikely that these installations will ever receive any subsidy.

A more detailed analysis of the political, economic, social, technological, environmental and legal boundary conditions of the Spanish energy sector in general and of the electricity sector in particular is presented in the deliverable D6.1 of the CHESTER project.

2.3.4. Future Perspective

The DH network in Ispaster is expected to expand in the future, so to supply other public buildings as well as 12 private apartments, which should increase the yearly heat load by 75 MWh and so improve the overall system efficiency. In this case a new biomass boiler would be added. At the time of writing (September 2018) the municipality has received a formal request from 11 out of 12 apartments' owners to connect their heating systems to the municipal DH. An agreement between the parties is expected to be reached during 2019 and, once solved the financial issues, the works to expand the DH network will start.

Regarding the electrical micro-grid, the possibility of connecting other buildings in the vicinity is currently under investigation, so to increase the electricity demand and reduce the curtailment of PV electricity production especially in summer.

Regarding the future boundary conditions at a regional level, the reader may refer to Section 2.6.4 (Lekeitio case).

At a national level, the radical shift from a fixed feed-in tariff to the fluctuating prices of the electricity market has significantly increased market exposure for RES projects, as their investment is secured based on the projected cash flows of the project itself. If renewable electricity is sold at pool prices, reliable and long-term electricity price forecasts play a key role for the debt financing of new installations of renewable electricity. However, electricity prices have been difficult to forecast in the long term, as they depend on multiple factors, such as macroeconomic variables, energy consumption, production capacity, interconnection between markets, trends in population, energy mix and public policies. Additionally, Spain has experienced very high volatility in electricity prices in the last four years [Sustainable City Network, 2018]. The current energy policy and legislation regarding RES is likely to be changed by the new government, who took office in June 2018. A much more RES-oriented energy policy is expected, including the abolition of the sun tax [Pirner, 2018].

A more detailed analysis of the political, economic, social, technological, environmental and legal boundary conditions of the Spanish energy sector in general and of the electricity sector in particular is presented in the deliverable D6.1 of the CHESTER project.

2.3.5. Potential of the CHEST System

The size of Ispaster entails that the potential CHEST system would be relatively small in comparison with the optimum design-size of CHEST. This has some implications from the energy and economic point of view:

- The total investment costs of the HP, the ORC and the HT-TES will be lower, although the specific investment cost (i.e. that per unit of capacity) would likely be higher due to the economies of scale. However, the scalability of the CHEST components and its effect on the investment costs are not known at this early stage, but they will be addressed later in other deliverables of the CHESTER project.

- As the CHEST system is smaller, a smaller volume will be needed for the HT-TES system (the energy content of a TES is proportional to its volume). On the other hand, the relative heat losses (i.e. with respect to energy content of the TES) in smaller TES are higher than in larger TES, because the absolute heat losses are proportional to the area of external surface of the TES and hence proportional to the volume at the power of 2/3.

Additionally, the implementation in Ispaster could be the opportunity to investigate the CHEST system as a valid alternative to the use of batteries to store electricity. The currently installed batteries have an efficiency of 70 %, so a CHEST system working with a round-trip efficiency of 100 % (as aimed at), would represent a significant improvement from an energy perspective. Moreover, the simultaneous presence of a DH network and buffer tanks could represent both a heat-source and a heat-sink for the CHEST system, optimizing the operation of the system depending on the season and the electricity/heat demand. For example, the surplus of electricity produced by the PV panels during daytime in summer could be used to run the CHEST heat pump, which could draw heat from the supply pipe of the DH network to store it at a higher temperature in the HT-TES. Then, the HT-TES could be discharged (e.g. later or at night or during cloudy days), producing electricity through the ORC system.

In other words, the presence of the CHEST system would not only make possible to match PV electricity production and electricity demand, but it would also increase the thermal load of the DH network —otherwise very low in summer—, so improving the efficiency of the DH system.

The requirements for the CHEST system would hence be:

- round-trip efficiency of storing electricity no lower than that of batteries (i.e. 70 %),
- storing capacity of the HT-TES (in terms of electricity) at least equal to the current battery capacity (i.e. 138 kWh),
- temperature levels of the HP and the ORC compatible with the current temperatures of the boiler and DH network, ideally evaporator temperature of the HP lower than 80 °C-75 °C and condensing temperature of the ORC higher than 55 °C.

2.4. Case Study #4: Barcelona, Spain

Barcelona is the capital and largest city of autonomous community of Catalonia. With a population of 1.6 million (as of 2017), Barcelona is the second most populous municipality of Spain, and its urban area, which extends to numerous neighboring municipalities, has around 4.8 million inhabitants.

The Barcelona districts of Forum and 22@ are covered by a district heating and cooling (DHC) network, whose construction started in 2003 and is owned and managed by the public-private company Districlima [Districlima, 2018]. The DHC network consists of two independent networks (two pipes each), and it is fed by two plants, generating both heating and cooling. One plant is located in the Forum district and uses steam coming from an urban waste to energy (WtE) plant; the second is located in the 22@ district. The DHC network supplies 102 large buildings —such as hotels, office buildings and tertiary buildings in general—, for a total roof surface of about 1,000,000 m^2 [Serrano, 2018].

The information presented in this section was made available by the company Aiguasol, partner of the CHESTER Consortium.

2.4.1. Energy Demand

District Heating and Cooling Demand

Some key parameters on Forum/22@ DHC network are listed in Table 10, while a map showing the area currently supplied by the DHC network is shown in Figure 13.

Table 10: Key figures on Forum/22@ DHC network.

Parameter	Value	Unit
Number of customers (substations)	102	-
Network trench length	16.8	km
Heating		
Yearly heat demand	29.0	GWh
Supply temperature	90	°C
Return temperature	60	°C
Cooling		
Yearly cooling demand	48.4	GWh
Supply temperature	5.5	°C
Return temperature	14	°C

The DHC network has continuously expanded since its construction started in 2003. From a contracted capacity of about 15 MW of heating and 19 MW of cooling in 2004, these have increased to 72 MW of heating and 104 MW of cooling in 2017. The network is expected to extended even further in the coming years, connecting new tertiary buildings such as the Can Ricard Area, the Mar Area hospital, the high-speed train station La Segrera and the campus Diagonal-Besós [Serrano, 2018].

The yearly heat demand of the DH network reported in Table 10 is the gross demand, so including the thermal losses from the network, which can be estimated in approximately 14 % of the yearly gross heat input to the network. The heat demand of the DHC network for the year

2017 was made available in the form of a time series with 1-hour resolution by Aiguasol, obtained extrapolating the yearly energy amount.

Electricity Demand

In 2016 the yearly electricity consumption in Barcelona was 6.6 TWh [Barcelona Municipality, 2018]. The same value can be assumed for 2017. An hourly electricity load profile for the city can be extrapolated from the hourly load profile at a national level, appropriately scaled down, so to match the yearly electricity consumption of the city. The hourly load profile at a national level refers to the 2017 gross electricity consumption and was made available by Aiguasol, retrieved from the operator of the electricity market in Spain.

2.4.2. Energy Supply

District Heating Supply

The demand of the DHC network is covered by two plants. The main plant (Forum plant) is located in the Forum district (on the right side in Figure 13), while a second plant (Tanger plant) is located in the 22@ district and it was conceived as a peak plant (in the center-top of Figure 13) [Serrano, 2018].

Almost the entire heat supply (and part of the cooling too) comes from the use of steam, produced by the WtE plant of Sant Adrià de Besòs, located right beside the Forum plant. In 2017, the WtE plant burnt about 369,000 tons of urban waste per year, with an average calorific value of 10.5±2.5 MJ/kg. The heat generated from the combustions is used to produce steam, which is used mainly for electricity generation, but partially also sold to the DHC network. The steam sold to the Forum plant for the DHC network is extracted from the 5.5 MW turbine, with a maximum extraction rate of 30 ton/hour, equivalent to 20 MW (4 steam/water heat exchangers of 5 MW each) [Serrano, 2018; TERSA, 2018]. Steam enters the heat exchangers at a temperature of 180 °C and exits as condensate with a temperature of 80 °C.

Additional heating capacity at Forum Plant is present in the form of a gas boilers with nominal capacity of 20 MW, while Tanger plant has 2 gas boilers of 13.4 MW. These are used as back-up boilers in case of peak demand (some hours in January and December, see Figure 11) and when the WtE plant is stopped for maintenance (3.5 weeks in July, see Figure 11).

Electricity Supply

Most of the steam produced in the WtE plant of Sant Adrià de Besòs is used for electricity generation in two turbo-alternators with nominal capacity of 26 MW and 5.5 MW respectively [TERSA, 2018]. The hourly profile of the gross electricity production from the WtE plant for 2017 was made available by Aiguasol, obtained extrapolating the yearly energy production.

Based on historical data of gross electricity production and electricity sales (Table 11), it can be estimated that the net electricity production is about 81 % of the gross electricity productions. The monthly net electricity production shown in Figure 11 was calculated in this way.

Some key parameters of the WtE plant are listed in Table 11 for the period 2013-2017.

The monthly heat supply to the DHC network (divided in steam and gas boiler contribution) and the estimated net electricity production from the WtE plant are shown in Figure 11. The low electricity production in June 2017 was due to the temporary halt of the WtE plant (3.5 weeks) for maintenance reasons.

Table 11: Key parameters of the WtE plant of Sant Adrià de Besòs in the period 2013-2017 [TERSA, 2018].

	2013	2014	2015	2016	2017
Treated waste (kton/year)	299.5	291.0	351.1	363.3	368.8
Capacity factor (%)	80.9%	73.3%	90.4%	91.3%	92.7%
Gross electricity production (GWh-el)	172.6	164.4	207.4	204.5	215.6
Sold electricity (GWh-el)	140.8	128.3	167.0	168.7	175.3
Steam sold to Districlima (kton/year)	76.3	75.1	75.8	78.0	95.5

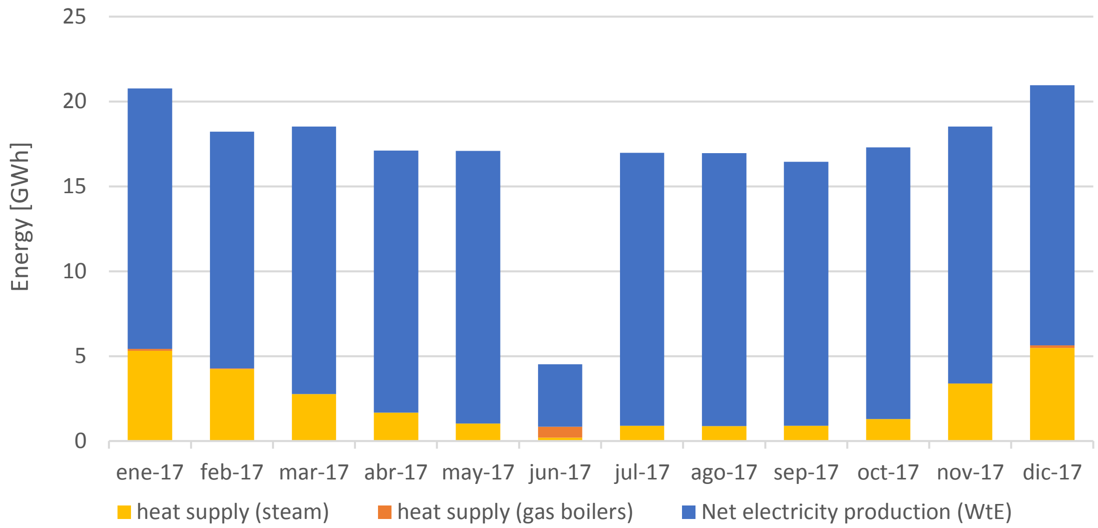

Figure 11: Monthly heat supply to the DHC network and electricity production from the WtE plant.

Energy Storage

Based on the collected information, no TES is present in connection to the heat supply of the DHC network. On the other hand, Forum Plant is equipped with a 5,000 m^3 water tank, but this is used in connection to the cooling supply of the DHC network and it is hence disregarded in this analysis.

2.4.3. Existing Boundary Conditions

In the metropolitan area of Barcelona there are two large combined-cycle plants for a total gross electric power of 2.6 GW and a yearly electricity production of 6.2 TWh (in 2011). Regarding RES, the main contribution comes from the treatment of urban waste and biomass, either by combustion or production of biogas [AMB, 2018].

Moving to a regional level, the net electricity production in Catalonia in 2017 was 44.9 TWh, hence covering 94 % of the regional consumption (47.7 TWh, including grid losses) [REE, 2018]. Nuclear energy was the main contributor, representing 53.5 % of the total production, followed by fossil fuel-fired combined-cycle plant (17.4 %) and CHP plants (11.7 %). Overall, the production of electricity with non-RES was 83.6 %. Among the RES, hydroelectric and wind were the main contributors, representing respectively 8.3 % and 6.2 % of the gross production [CAEN, 2018].

The present situation in the country does not favor the installation of new renewable power facilities, after that the Spanish government in 2012 canceled incentives for new renewable electricity installations. For a more comprehensive description of the current situation of the energy sector in Spain, the reader should refer to Section 2.3.3.

In Spain, the regulated electricity market is composed by several markets, where market agents buy and sell electricity. This organized market includes a day-ahead market, followed by six intraday auctions. Most of the operations happen around the OMIE (the operator of the Iberian electricity market), where short-term operations take place. The geographical scope of the market is the entire Iberian Peninsula, being Spain and Portugal part of an integrated market, the Iberian Electricity Market (MIBEL) market. The day-ahead spot market is currently coupled with Portugal and North-West Europe region.

Concerning the wholesale power market in the Spanish zone, in 2017 around 253 TWh were sold in the day-ahead spot market (192 TWh excluding bilateral agreements), while 31 TWh were sold in the intraday market. The weighted average spot market price was around 60.6 €/MWh in 2017 (25.1 % higher than in 2016), and the daily market price represented 88 % of the final price. The share of bilateral agreements is around 24 %, with no significant evolution from the last years [REE, 2017].

2.4.4. Future Perspective

Although the current energy mix both at a local and regional level presents a relatively low share of RES for electricity generation, the situation is likely to change in the coming years. In fact, on August 1, 2017 the Catalan Parliament approved the law 16/2017 on climate change. The law requires not only the decarbonization of the energy system, but also its denuclearization, which should take place by 2027. The goal is to build an energy system based entirely on RES by 2050. These objectives are also in agreement with the energy policy proposed at a national level by the new government who took office in June 2018 [Pirner, 2018].

However, the lack of a clear energy strategy in the short and long term introduces large uncertainties on the future evolution of the electrical sector. Only a draft of a “Climate Change and Energy Transition Law” has been presented in mid-2018 to the Spanish Parliament, but the change of the government is likely to cause significant delays on its final approval.

Uncertainty related to the key concept of reasonable rate of return (RRR) remains, increased after the retroactive cut of the PV subsidies in 2013. To avoid political interference with the system’s costs in the future, the principle of “no new cost without a revenue increase” should be strictly enforced [IEA, 2016].

There is no evidence on how the new government will tackle the shutdown of nuclear plants which are already at the end of their lifetime, or how they will tax fossil fuels (coal plants contribute with a significant share to the electricity generation).

2.4.5. Potential of the CHEST System

Considering the current operational regime of the WtE plant and of the associated DH network, the potential of the CHEST system for the Barcelona case study seems limited at the present time, also due to the low penetration of RES electricity in the region (see Section 2.2.3) and the high electricity prices, with limited variations between peak and off-peak hours (Figure 12). This situation may however change in the future, if the planned decarbonization and denuclearization of the energy system is carried out (see Section 2.4.4). If fossil fuel plants were shut down and the share of fluctuating RES electricity increases, the possibility of matching the supply and demand through supply-side management would be limited. Hence, energy storage technologies could play a crucial role and CHEST could be one of them.

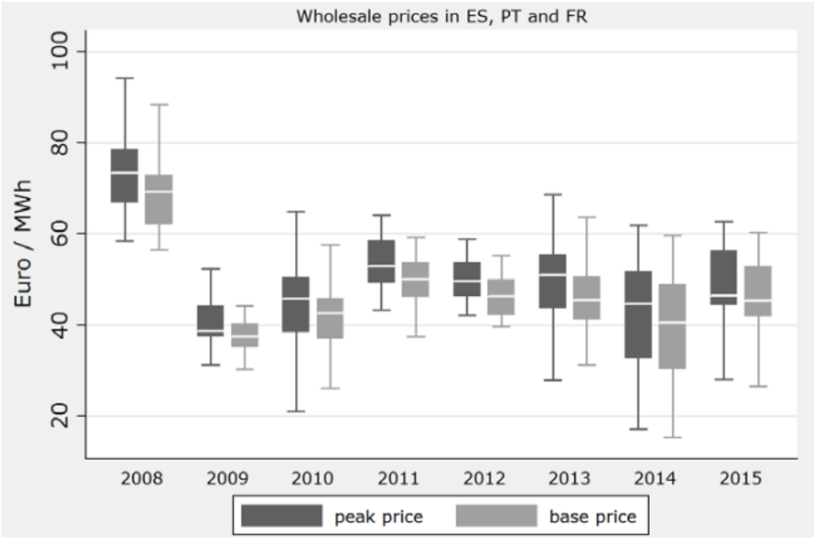

Figure 12: Wholesale electricity price in Spain, France and Portugal 2008-2015 [Breitschopf, 2016].

The goals of the WtE plant in Barcelona are, in order of decreasing priority, to burn the urban waste, supply heat to the DH network and produce electricity. In fact, the electricity generation entails significant operational costs, without increased benefits over the heat generation. In a future scenario with a high share of fluctuating RES electricity, there would be an increasing number of hours with excess and cheap electricity fed into the grid. In this scenario, a CHEST system would provide a possibility for regulation. As the operation of the HP requires heat, the WtE would decrease its electricity output in favor of the heat production. Simultaneously, the HP would absorb electricity from the grid. Both the decreased electricity production from the WtE and the electricity consumption of the HP provide downward regulation to the electrical grid, so helping match supply and demand. Another advantage offered by the CHEST system would be that the WtE could keep on burning the urban waste at constant load. On the other hand, when the RES electricity is not able to cover the demand, the CHEST system could feed electricity into the network through the ORC, instead of the TSO activating fossil fuel-fired backup plants. Depending on the operation mode, the ORC could either prioritize the electricity production using the low temperature sea water at the condenser, or produce less electricity and higher temperature condensing heat, which could be injected in the DH network. The WtE would then be required to deliver a lower thermal power to the DH network and could increase the electricity output. In both cases the presence of the CHEST system allows upward regulation.

The CHEST system could interact with the WtE and/or DH network either directly or through a buffer storage, but a large-scale TES, which could be expensive to build in an urban area such as Barcelona, would be not be required.

In case of a high share of PV electricity, which would be feasible in a country like Spain, the CHEST system could run in charging mode during daytime and in discharging mode at night. This would result in a high number of cycles per year and provide a good business case.

Another scenario, which seems not to be unlikely based on the recent developments, could be a significant increase of the DH network, thanks to the connection of new buildings. In fact, in the last years, the municipality has shown interest in extending the DH network, by investing in additional piping to expand the covered area. Overall, it can be expected that in the future there will be a higher DH demand, and that this will be covered by the WtE plant, by reducing the current electricity production. The WtE plant currently gives priority to the heat supply to the DH network rather than to the electricity generation. This approach will most likely continue in the future, because it is in the interest of both the WtE operator (as explained above) and the DH operator, for whom the WtE plant provides cheaper and less carbon intensive heat compared to the backup boilers. So, both parts would most likely agree on a higher heat supply, if the DH demand was to increase. In this scenario, it could become feasible to integrate a large TES in the DH network, to help matching the heat demand and the waste heat supply, as well as reducing the operation of the more expensive and more carbon-intensive operation of the gas boilers. In this respect, a CHEST system could also be integrated in connection to this large-scale TES.

Figure 13: Forum/22@ DHC network and heat generation plants (green/white squares) [Serrano, 2018].

2.5. Case Study #5: Alpha Ventus Wind Farm, Germany

2.5.1. Background of the case study

The Alpha Ventus wind farm was the first offshore wind farm in Germany and therefore it has also served as a test field to gain more knowledge and experience on offshore wind power. The farm is located in the North Sea, around 45 km north of the isle of Borkum and consists of 12 wind turbines of 5 MW each. The wind farm has delivered almost 2 TWh of electricity since the start of operation in 2010.

There is an offshore electric power transformation and power factor correction station, where the voltage of 30 kV AC coming from the wind turbines is transformed into 110 kV AC. This reduces the electric losses during the 60 km long power transport via sea cable to the coast. From the wind farm, the cable passes through the isle of Norderney until the coastline at a point named Hager Marsch, located about 5 km northeast of the town of Norden. At Hager Marsch there is an onshore electric power transformation and power factor correction station, where the electricity coming from the wind farm is fed into the German electrical grid [Alpha Ventus, 2018].

At the moment there is no existing DH network in the vicinity of the wind farm and also no major electricity consumer. A part of the electricity from the wind farm is used in the town of Norden (25,000 inhabitants), but eventually electricity consumption is not clearly attributable, as the produced electricity is just fed into the grid.

The idea of this case study was to look at possible consumers of electricity and heat that are located near Hager Marsch. Besides the town of Norden nearby, another potential consumer is the town of Emden (about 50,000 inhabitants), which lies about 40 km from Hager Marsch. Furthermore, there are industrial consumers such as the Volkswagen production facility and factories in the port of Emden.

During the investigations and data requests for this case study, it was found out that the towns of Norden and Emden take part in a national climate protection program, which aims at increasing the share of RES generation.

Emden has a lot of onshore wind turbines and PV installations, which already generate more renewable electricity than needed (on a yearly basis). Wind power is to be further developed, with excess electricity possibly used for heating purposes (sector coupling between the electricity and heating sectors) [Emden, 2017]. Moreover, there are two or three DH networks for parts of Emden and considerations to expand this network structure [Emden, 2018].

Also, the town of Norden has some onshore wind turbines and PV installations, while another part of the electricity— as well as heat— demand is covered by a CHP plant [Norden, 2018].

2.5.2. Comments on data used for the case study

Unfortunately, the requests for high resolution data of electricity and heat demands of the two towns or parts of them were not successful. The municipalities of Emden and Norden only get yearly data for their analyses in the above-mentioned climate protection program. The energy providers have data in higher resolution only for selected industrial consumers, however data for single users cannot be issued due to privacy protection. Aggregated data for several industrial consumers was refused by the energy providers because of lacking personnel resources.

As currently there is no real connection between energy generation (Alpha Ventus wind farm) and energy consumption (Norden, Emden), it was decided to use the data from a DH system in the town of Crailsheim (Germany), which has been monitored by the University of Stuttgart for several years now. The DH system supplies heat to an area mainly consisting of single-family houses and some smaller commercial buildings. Heat load, supply and return temperatures as well as data for the heat sources and thermal storage are available in 1-hour resolution for 2014. The year 2014 was chosen, because the area supplied by the network was most properly defined at that time (there have been several expansions of the network since) and monitoring data deficiencies were lowest in this year. As the corresponding electricity consumption of this area is not monitored by the University of Stuttgart and the energy provider could not release the data, synthetic load profiles with a time resolution of 1 hour were generated based on the information available about the electrical consumers in this area.

Data on the hourly electricity generation and curtailment of Alpha Ventus wind farm were requested from the Alpha Ventus consortium [RAVE, 2018]. These will be made available, but with distribution restrictions. Depending on the data quality, the data from either 2013 or 2017 will be used. The price of electricity was requested through the Fraunhofer Institute for Solar Energy Systems [Fraunhofer ISE, 2018]. Mean intraday spot electricity market prices were made available in 1-hour resolution for both 2013 and 2017.

2.5.3. Energy Demand

District Heating Demand

Figure 14 shows the area of Crailsheim supplied by the DH network in 2014. This is a residential area with 199 single-family houses. Additionally, there are a school with an adjacent gym (bottom-left corner in Figure 14) and some commercial buildings (top-left corner), such as a bakery, a hotel, some offices, a restaurant, a café and some smaller shops.

Figure 14: View of the area supplied by DH in Crailsheim (buildings within the red-dashed lines).

In 2014 the heat demand of the district was about 4,900 MWh (including heat losses), with average supply and return temperatures of 73 °C and 49 °C respectively. Figure 15 shows the monthly heat demand in 2014, as well as the monthly average supply and return temperatures.

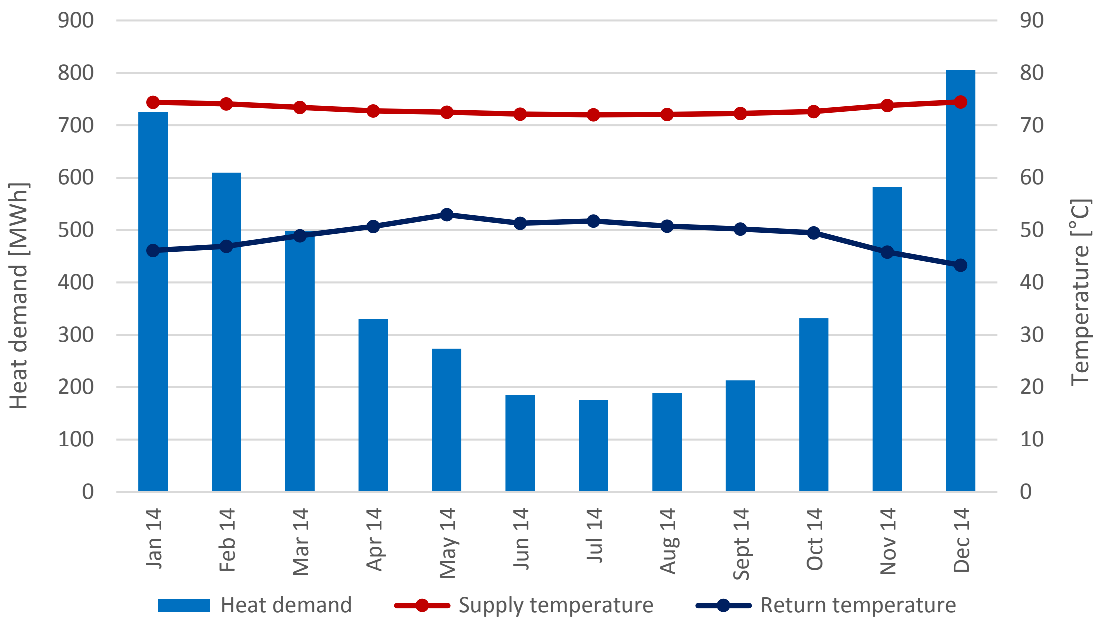

Figure 15: Monthly heat load and average supply and return temperatures of the DH network in 2014.

The monthly-averaged supply temperature was almost constant over the year, while the average return temperature showed a minor seasonal dependence. When considering the absolute minimum and maximum values in 2014, the supply temperature varied in the range of 67-78 °C, while the return temperature has higher fluctuations, ranging from 25 °C to 67 °C.

The DH network described above has expanded several times in the last years and it will probably further expand, reaching new consumers. Hence, also the heat demand increased from about 4,700 MWh in 2012 to 6,900 MWh in 2016, as Figure 16 shows.

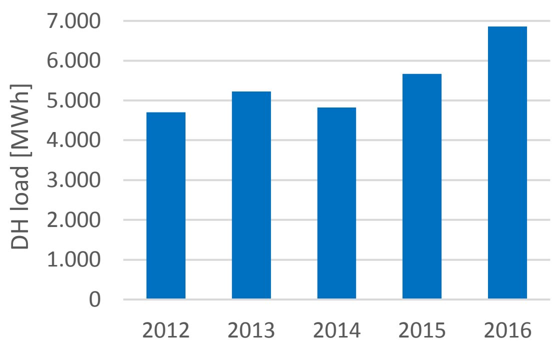

Figure 16: Development of the heat demand of the DH network in Crailsheim in the period 2012-2016.

Electricity Demand

No monitoring data of the electricity demand for the area were available, so synthetic load profiles were generated. To do so, the following procedure was used. First, the different types of consumers were identified. These were the 199 single-family houses, the school, the gym, the commercial buildings and the street lights. For each of these four consumer types, an hourly and a monthly dependence of the load was elaborated. In case of the singly-family houses, this was based on the findings of [Tjaden, 2015]. The electricity demand from the street lights was calculated assuming reasonable values for their number, power and a switch-on/off time schedule dependent on the month of the year. The electricity demands of the school and the gym were estimated based on average values for Germany and through realistic time schedules. A similar procedure was chosen for the commercial consumers.

As a result, load profiles with 1-hour resolution for all these consumers were generated. In Table 12, the yearly electricity demand of the different consumers is presented. The single-family houses account for about the half of the electricity demand, followed by the commercial buildings.

Table 12: Yearly electricity demand of the different consumers for the area supplied by DH.

Consumer	Electricity demand (MWh/y)
Single-family houses	726
School	99
Gym	50
Street lights	29
Commercial buildings	484
Sum	**1,388**

2.5.4. Energy Supply

District Heating Supply

Figure 17 shows the hydraulic scheme of the DH network in Crailsheim. Several solar collector arrays and a heat pump act as heat generators, while two hot water tanks, a borehole TES and the DH grid Hirtenwiesen II act as heat consumers. The 4,900 MWh of yearly heat demand mentioned in Section 2.5.3 refer to the DH grid Hirtenwiesen II. Because the solar thermal collectors and the heat pump do not cover the entire heat demand of Hirtenwiesen II, additional heating is provided by the DH grid Hirtenwiesen I (see Figure 17), which is supplied by a thermal plant. The DH grid Hirtenwiesen I can also be used as heat sink by the grid Hirtenwiesen II, as excess heat can be transferred from Hirtenwiesen II to Hirtenwiesen I, when there is a too high solar thermal output. In this way, collector stagnation is prevented.

The DH system Hirtenwiesen II in Crailsheim represents the largest solar DH plant with seasonal TES in Germany. In 2014, the solar collectors generated about 1,960 MWh (about 40 % of the total DH heat demand of 4,900 MWh). The collectors are mounted on two noise protection earth walls as well as on several buildings, with a total aperture area of about 7,500 m^2.

The heat pump has an electrical power of 80 kW. As seen in Figure 17, the heat pump is hydraulically integrated between the two hot water buffer stores. This enables long operation cycles, since the heat pump works with large volumes on both evaporator and condenser side. Furthermore, drawing heat from the buffer store 2, the heat pump lowers the temperature of this storage, which increases the efficiency of the solar collectors. As the heat pump does not exchange heat with the environment, its energy input into the system is only due to its electrical power input. In 2014, the heat pump's electricity consumption was about 250 MWh.

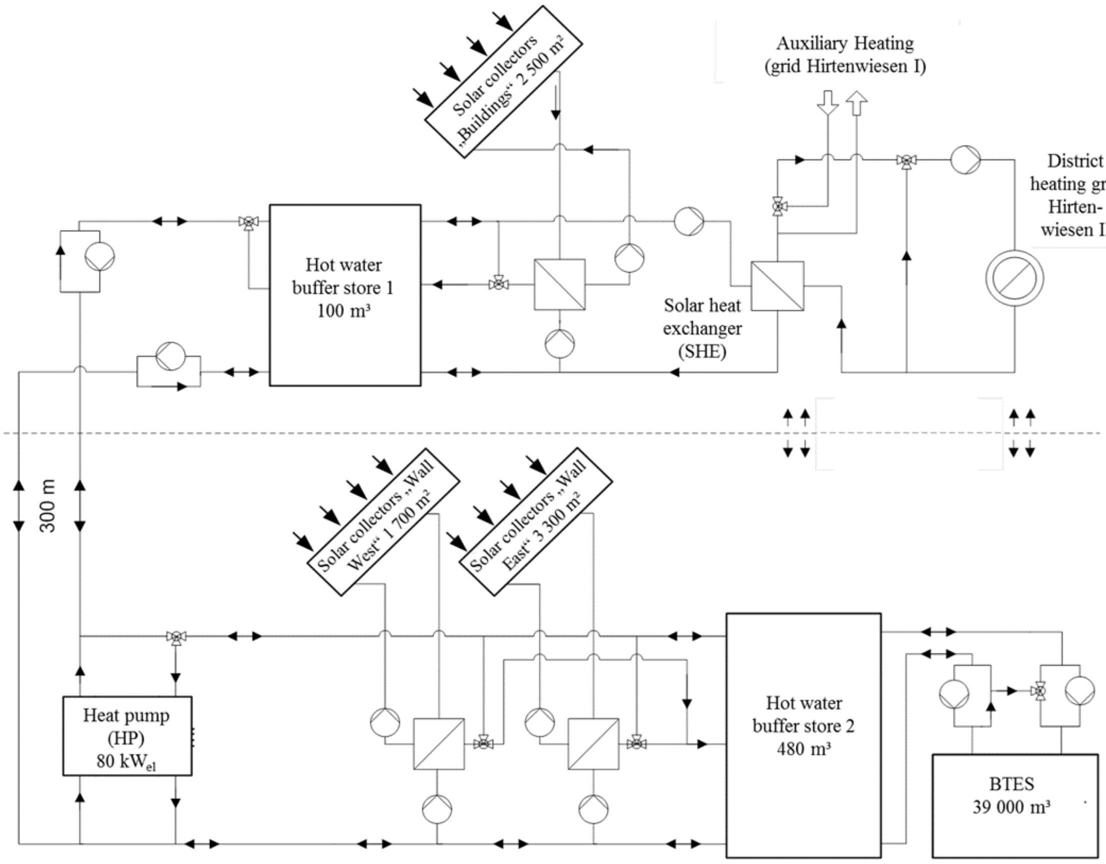

Figure 17: Hydraulic scheme of the DH network in Crailsheim [Gohl, 2017].

The remaining heat demand of Hirtenwiesen II (about 2,600 MWh/year) comes from the DH grid Hirtenwiesen I. Amounts and temperatures of the different heat sources are available in 1-hour resolution.

Electricity Supply

The wind farm Alpha Ventus consists of 12 wind turbines with a nominal power of 5 MW each, for a total power of 60 MW. Being the first offshore wind farm in Germany, this was to be used also as a test field for further offshore wind projects. Hence, two types of wind turbines were installed, whose main parameters are listed in Table 13.

Table 13: Technical data of the two types of wind turbines at Alpha Ventus [Alpha Ventus, 2018].

	Senvion 5M (REpower)	Adwen AD-5-116
Nominal power (MW)	5	5
Number of turbines (-)	6	6
Rotor diameter (m)	126	116
Hub height (m)	92	90
Nominal wind speed (m/s)	13.0	12.5
Turn on wind speed (m/s)	3.5	3.5
Turn off wind speed (m/s)	30	25
Fixation type	Jacket	Tripod

The technical data of the two types of wind turbines are relatively similar, with the main differences being the type of fixation. Due to rough offshore conditions, the lifetime of the turbines is estimated to be 20 years.

The average yearly electricity generation of the wind farm is about 250 GWh, which is equivalent to about 4,150 full-load hours or a capacity factor of 47 %. This is higher than the performance that was originally expected, i.e. 220 GWh or 3,700 full load hours, corresponding to a capacity factor of 42 % [Alpha Ventus, 2018].

Energy Storage

As seen in Figure 17, there are three storages in the DH system: a borehole TES with a volume of 39,000 m^3 (water equivalent of 10,000 m^3) and two hot water tanks with a volume of 480 m^3 and 100 m^3 respectively. The lower part of the system in Figure 17 —which consists of the two earth wall collector fields, the buffer storage 2 and the borehole TES— is mainly thought for seasonal operation, i.e. solar excess heat in summer is stored in the borehole TES to be used in winter. The buffer storage 2 is necessary, because the thermal power output of the collectors is higher than the charging capacity of the borehole TES. Hence, the collectors do not charge the borehole TES directly, but through the buffer storage 2. In 2014, about 720 MWh of heat were transferred into the borehole TES, while about 310 MWh were taken out, which corresponds to an efficiency of 43 %. This low efficiency is due to the limited charging and discharging power of the borehole TES.

Besides their function to store heat from the solar collectors, the two hot water storages also serve as heat source (buffer storage 2) and sink (buffer storage 1) for the heat pump. Furthermore, if necessary, thermal energy can also be transferred between the two buffer storages [Gohl, 2017]. For example, heat can be transferred from buffer storage 1 to buffer storage 2, to prevent stagnation for the collectors installed on the buildings. In general, the upper part of the system is designed to cover the base load of the DH network Hirtenwiesen II.

2.5.5. Existing Boundary Conditions

District Heating

Currently in Germany DH supplies about 5.7 million households, which correspond to 14 % of the total number of households. Every year, the number of households supplied by a DH network increases by about 75,000 [Recknagel, 2018]. About 83 % of the DH heat supply comes from CHP plants. Thermal plants provide about 15 % of the heat fed into DH networks, while the remaining 2 % comes from industrial waste heat [AGFW, 2016].

The use of RES in DH systems is still limited. In 2015 the main energy sources for DH systems were natural gas (36 %), hard coal (34 %), lignite (13 %), biomass (5 %), waste and others (12 %) [Degenhart, 2017]. However, it should be noted that there are several possibilities for DH systems to receive financial incentives, especially when RESs are used.

First, the German Act for the support of RES in the heat sector (EEWärmeG) includes financial support for solar thermal systems, biomass plants, geothermal energy, TES and DH networks [Bundesministerium der Justiz, 2015b]. Secondly, the German Act for the conservation, modernization and expansion of combined heat and power (KWKG) ensures payments for the electricity generated by CHP plants, but it also supports new and expanded DH networks and TES [Bundesministerium der Justiz, 2017]. The market incentive program (MAP) is another measure to support RES, but also DH networks and TES. There are different funding conditions for private applicants, companies and municipalities. Financial support can be in the form of direct payment of a share of the investment costs or in the form of a loan with reduced interest rate [Bundesministerium für Wirtschaft, 2018a]. Finally, there are also possibilities for support through programs at regional or municipal level, e.g. the program "Energieeffizienze Wärmenetze" (Energy efficient heating networks) in the federal state of Baden-Wuerttemberg [Baden- Württemberg, 2018].

Electricity

Electricity production in Germany is still dominated by fossil fuels, such as coal (especially lignite) and natural gas, as well as nuclear power. However, RESs have continuously increased their share in the electricity production, from 3.4 % in 1990 to 36.2 % in 2017. In fact, Germany's energy transition has focused mainly on the electricity sector, while the share of RES in the heat sector and in the transport sector is rather low, accounting for 12.9 % and 5.2 % in 2017 respectively [Bundesministerium für Wirtschaft, 2018b].

Although the wholesale prices for electricity are not particularly high in Germany, several taxes, surcharges and fees result in one of the highest consumer electricity prices in Europe. For private households the electricity price was about 30.5 c€/kWh (including all taxes) in the 2nd half of 2017, while for industrial consumers the price accounted for about 12.7 c€/kWh (including consumption tax, but without VAT) [Statistisches Bundesamt, 2018].

A key act to support renewable electricity production is the Renewable Energy Sources Act (EEG). This act regulates for instance obligations of grid operators to connect plants generating renewable electricity and feed-in remunerations [Bundesministerium der Justiz, 2015a]. For offshore wind farms the starting feed-in remuneration (paid during the first 12 years of operation) currently accounts for 15.4 c€/kWh. After 12 years, the remuneration is 3.9 c€/kWh. Wind farms, which start operating after 2021, however, will have to apply for financial support. The newly installed offshore capacity is limited and made available via tenders. For the period 2021-2025 about 3.1 GW will be tendered, followed by 0.7-0.9 GW per year in the period 2026-2030. The goal is to reach 15 GW of installed offshore wind farm capacity in 2030 [BWE, 2018].

More details about the situation and regulation of the German electricity market can be found in the deliverable 6.1 of the CHESTER project.

2.5.6. Future Perspective

District Heating

As shown in Figure 16 the heat demand of the DH network in Crailsheim has increased over the last years and will probably experience a further increase in the future. Regarding the original location of this case study, i.e. the towns of Emden and Norden, DH networks are present in Emden and will be expanded. New DH networks may be built in Norden in the future.

From a national perspective, heating via DH increases slowly. From the year 2000, the total length of DH networks increased by 17 %, from 18,326 km to 21,521 km in 2016, while the installed thermal energy generation capacity remained almost constant at around 50,000 MW [AGFW, 2016].

The use of RES in DH networks is likely to increase, so to contribute to the ambitious energy transition and climate protection targets. The share of RES in the final energy consumption for heating and cooling is to increase to 14 % in 2020 [Bundesministerium der Justiz, 2015b]. The long-term goal for the year 2050 is the reduction of the total GHG emissions by 80-95 % compared to 1990 [Bundesministerium für Umwelt, 2017], which definitely calls for efforts to reduce the use of fossil fuels in the DH sector.

The increase in the use of RES in the heat sector is currently slow, despite the support schemes mentioned in Section 2.5.6. Biomass production is limited. Solar thermal or wind energy via power-to-gas or power-to-heat seem more suitable technologies for the increase of renewable heat in DH systems. Financing of the use of RES in DH is still difficult, e.g. due to the high investment costs [Degenhart, 2017].

A general trend in DH systems (not only in Germany) is the ongoing decrease of the supply and return temperatures. Modern DH networks operate with supply temperatures of about 40-80 °C and return temperatures of about 30-50 °C [Degenhart, 2017; Rühling, 2018]. DH networks of the next generation (so-called "cold DH") may supply heat at even lower temperatures, which reduces the heat losses from the network and allows for cooling purposes, but requires decentralized reheating, usually by means of heat pumps [Rühling, 2018; Bestenlehner, 2014]. The lower supply and return temperatures are also advantageous for the integration of RES [Degenhart, 2017].

Offshore wind energy

The wind farm Alpha Ventus had an operation permit for 20 years, which corresponds to the expected lifetime of the turbines. Consequently, the wind turbines installed in 2010 should be decommissioned in 2030 [Alpha Ventus, 2018].

After Alpha Ventus, several other wind energy projects have followed. For instance, the wind farm "Riffgat" with 30 wind turbines with a nominal power of 3.6 MW each was completed in summer 2013 and began to supply electricity to the grid in February 2014. Another even bigger project was "Amrumbank West" with 80 wind turbines of 3.6 MW each, completed in October 2015. Further projects were "Borkum II", close to Alpha Ventus, and DanTysk&Sandbank [Alpha Ventus, 2018]. Other projects are currently in the planning or erection phase, both in the North Sea and in the Baltic Sea [Wikipedia, 2018]. This has led to a large increase of electricity generated by offshore wind farms in Germany in the last years (Figure 18). In 2017 almost 18,000 GWh of electricity were generated by offshore wind farms, which corresponds to 3 % of the total German gross electricity generation [Bundesministerium für Wirtschaft, 2018b].

As mentioned above, the funding conditions for offshore wind energy in Germany will change in 2021, meaning that newly installed capacities will be limited and made available through call of tenders. Another important fact to keep in mind is that in Germany —unlike for instance Great Britain and the Scandinavian countries— wind farms must be built relatively far away from the coast for legislative reasons [BWE, 2018]. This leads to increased costs for both construction and connection to the grid, as well as to higher electric losses during transmission. The restriction of the available sites for wind farms together with the limited new capacity to be installed and a reduced funding scheme could lead to a slow-down of the growth of offshore wind farming in the coming years.

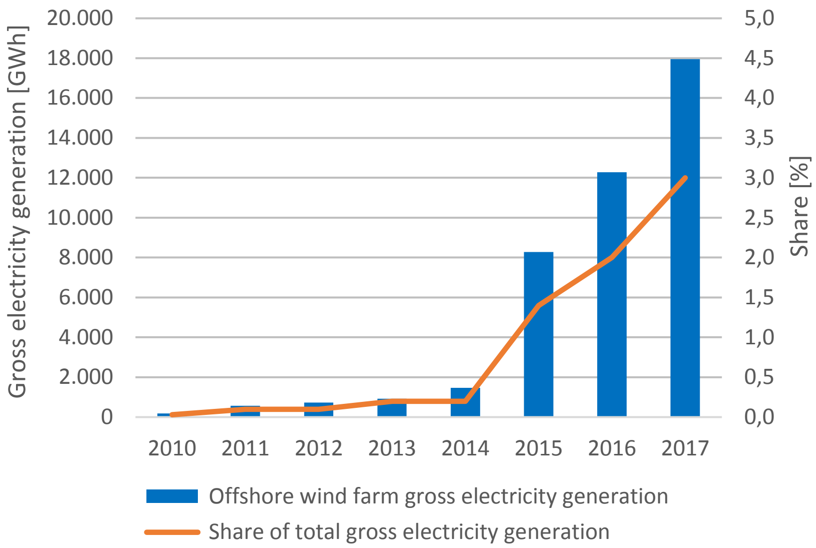

Figure 18: Development of the gross electricity generation from offshore wind farms in Germany [Zeitreihen Erneuerbare, 2018].

2.5.7. Potential of the CHEST System

The special feature of the Alpha Ventus case study is the availability of excess electricity generated by Alpha Ventus wind farm. This electricity could be used to run the heat pump of a CHEST system or could also be directly converted into heat to further increase the share of RES in the heat supply of the DH network. On the other hand, the thermal output from the solar collectors can serve as heat source for the CHEST system.

The borehole TES is unlikely to act as low-temperature storage for the CHEST system, because of the low charging and discharging power. However, it should be considered on the heat source side, when determining the potential of the CHEST system in comparison to the current situation without CHEST system with the help of the intended performance simulations.

Power-to-heat considerations are gaining more and more attention for the town of Emden, which already has excess power, mainly from wind energy, and intends to build even more wind turbines. In fact, the Alpha Ventus case study represents a situation, which will become more common in northern Germany in the future, i.e. more frequent excess of electricity due to the wind power capacity, but relatively few electricity consumers. The current solution to this problem (and indeed a controversial discussion in Germany) is the construction of new transmission lines from the generators in the north to the consumers in the south. More details on this are given in the PESTEL analysis of Germany in the deliverable 6.1 of the CHESTER project.

Considering the figures of energy supply (about 250 GWh electricity per year) and demand (4.9 GWh of heat and 1.4 GWh of electricity) given in the previous sections, it is clear that for such a virtual integration of the CHEST system with the wind farm most of the electricity generated by the offshore wind farm must be fed directly into the grid. So, when carrying out the performance simulations, business case considerations and economic assessments planned for other tasks of the project, some scaling of these figures should be made.

Several interesting questions need to be answered in the upcoming tasks related to this case study. For instance, it should be checked how suitable the electricity supply profiles of the wind farm are with respect to the operation of the CHEST system. Furthermore, a cost-benefit analysis from an energetic, environmental, but also economic point of view should be carried out, to clarify if it is preferable to store part of the generated electricity in a CHEST system or feeding all into the grid. The CHEST system could also help reduce the curtailment rate of the wind farm and balance the electrical grid. In general, the CHEST concept could be an alternative to new expensive transmission lines.

2.6. Case Study #7: Lekeitio, Spain

This case study represents a Strategic Energy Project that has been planned for electric and thermal supply for the town of Lekeitio, located in the Basque Country (Spain), 53 km northeast from Bilbao. The municipality has 7,293 inhabitants (as of 2005) and is one of main fishing ports of the Basque coast.

It is mainly a residential and services town with almost no industries. Being a touristic place, it has more than 20,000 people in summer, which entails a high demand of DHW.

As in the case of neighboring Ispaster (Section 2.3), the goal is to cover about the half of the heat and electricity demand through renewable energies, more precisely forest residues from the surrounding woods, solar thermal collectors and PV panels. Being a project, there is no plant or facility installed nowadays, and it is not defined whether and when the project will actually be developed.

The project has been thoroughly studied by the local company EZE Barrizar, who has also provided the technical information presented in this section [EZE Barrizar, 2017a].

2.6.1. Energy Consumption

District Heating Consumption

The DH network is expected to be 4 km long and should cover an area of approximately 1 km^2. The design supply/return temperature are 75 °C/55 °C. The yearly heat demand of the town is estimated in 17 GWh for the considered area, but the network could possibly be expanded in a second moment to cover a larger area.

The drying processes of the forest residues would represent an additional heat demand and the sale of dry biomass for individual biomass boilers with high added value would represent another source of revenue for the project.

Electricity Consumption

The estimated yearly electricity consumption is 18 GWh.

2.6.2. Energy Supply

District Heating and Electricity Supply

The main energy source is planned to be biomass —in the form of forest residues— collected from the woods surrounding the town. It is estimated that almost 35,000 tons of forest biomass can be collected locally each year. The biomass would be exploited in a complete gasification and cogeneration plant. After being treated, the forest residues would be converted into syngas, through the “Enamora” gasification technology, developed by the company Guascor [Guascor, 2009]. A scheme of the Guascor plant is shown in Figure 19. The result of this gasification process is a syngas with low calorific value (about 5 MJ/m^3), which would then be burnt in a specially adapted Alternative Internal Combustion Engine with a nominal power of 2 MW-el. The plant is expected to consume about 13,000 tons/year of forest biomass.

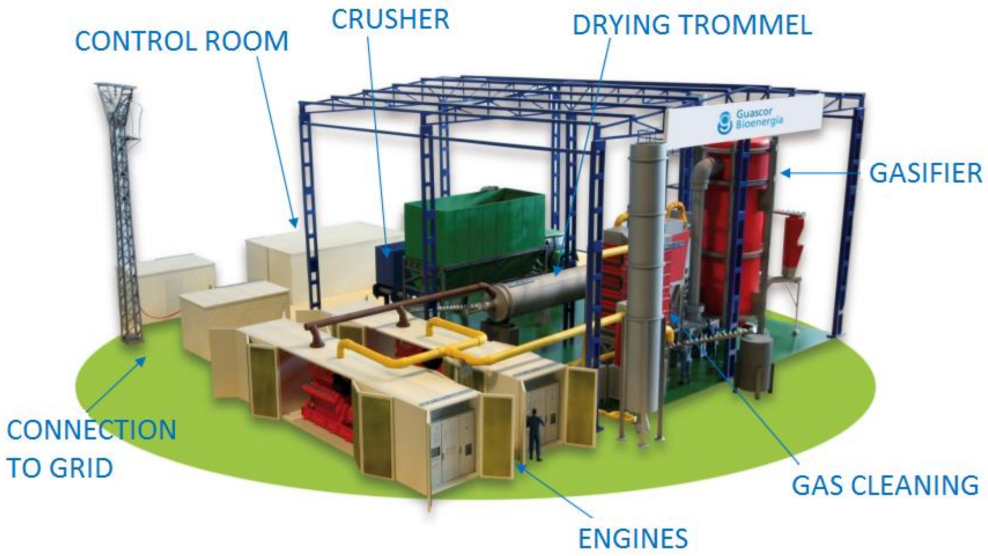

Figure 19: Scheme of the Guascor gasification + CHP plant [Guascor, 2009].

The engine would produce both electricity and heat, with an estimated yearly output of 12.7 GWh-el and 12.6 GWh-th. Part of this energy would be supplied to the plant treating the forest residues, to make them suitable for the gasification process: the residues must be grinded into small pieces (2-15 mm) and the humidity content lowered to <10 %, which requires a lot of heat for drying purposes. So, the net heat which could be fed into the DH network would be about 10 GWh/year (59 % of the demand), while the available electricity would be about 8 GWh (44 % of the demand). The principle scheme of the biomass cycle in Lekeitio project is shown in Figure 20.

The biomass treatment plant is expected to produce not only biomass suitable for the gasification process, but also wood chips which could be sold to be used in privately owned biomass boilers. This additional source of revenues would improve the economic feasibility of the project.

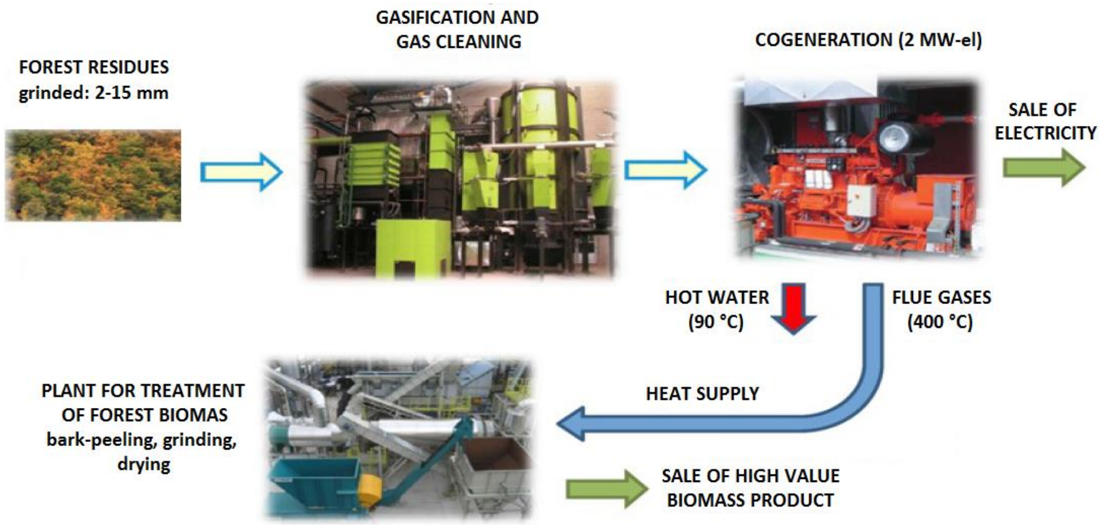

Figure 20: Principle scheme of the biomass cycle in Lekeitio project [Barrizar, 2017b].

Another source of thermal energy would be the solar thermal collectors, while additional renewable electricity would come from PV panels. Both solar thermal collectors and PV panels could be distributed over several roofs available (see Figure 21).

Solar thermal collectors —most likely with the same vacuum tube + CPC technology as in Ispaster (see Section 2.3) — are planned to be installed for a total capacity of 4 MW. Water would be used as solar collector fluid so, if too low temperatures occurred in winter, the circulation pump would be activated to avoid freezing. The expected yearly energy output is 3.6 MWh, of which 1.2 MWh self-consumed locally and 2.4 MWh supplied to the DH network.

The planned installed capacity of PV panels is 1 MW. The expected energy output is 0.9 GWh/year, corresponding to 5 % of the town's electricity demand.

Figure 21: Potential roof area for PVT installation in Lekeitio [Barrizar 2017b].

2.6.3. Existing Boundary Conditions

In the Basque Country industry is the major energy consumer (42 % of the final energy consumption), followed by power generation and transport. Services and residential buildings together account for 20 %. In 2014, RES represented approximately 7 % of the energy demand (it was 3.9 % in 2000) [Energy Transition Platform, 2016]. Over 80 % of the renewable energy comes from biomass and biofuels, and the largest demand for renewable energy is related to industry, mainly to the paper sector.

Electricity accounts for approximately 26 % of final energy consumption in the Basque Country and in 2014 the total electricity demand in the region was 16.3 TWh. Of this, 14 % was imported, while 6.5 % came from RES (hydro, 2.6 %; wind, 2.1 %; biomass, 1.6 %; PV, 0.2 %). The installed capacity of wind and hydro power has remained stable in the last decade (173 MW and 153 MW respectively). The PV capacity has increased to 24 MW, but a reduction in biomass installed capacity (currently 46 MW) has entailed that the total installed capacity of renewable electricity has not increased since 2010 [Basque Government, 2015].

Despite the low installed wind capacity (0.6 % of the national capacity), the Basque Country hosts the headquarters of Iberdrola and Gamesa, two of the biggest players in the wind sector. Overall, in the Basque Country 112 firms operate in the wind energy sector, employing 15,000 people [Cluster Energia, 2017].

The present situation in the country does not favor the installation of new renewable power facilities, after that the Spanish government in 2012 canceled incentives for new renewable electricity installations, also to reduce the tariff deficit [Basque Government, 2016]. For more details on the current situation of the energy sector in Spain, the reader should refer to Section 2.3.3.

2.6.4. Future Perspective

Being just in a planning/designing phase, the entire Lekeitio project can be considered as a "future perspective". However, if the project is implemented in the presented form, possible developments to further increase the share of RES have already been considered. These include the exploitation of a 90 m elevation difference of a near mountain to install a small hydroelectric power plant, after installing an underground water storage on the top; the exploitation of wind resources through new-concept bladeless wind turbines [Vortex, 2018]; the exploitation of wave energy; the production of biogas starting from organic non-forest residues, which are currently available (e.g., from agriculture-industries and wood treatment) for an estimated amount of 10,000 tons/year.

On a regional perspective, the technological advances seen in the RES sector hold out the promise of having locally-generated renewable energy in the future. However, in the short and medium-term, the affordability of alternative energy sources is unlikely to radically change the current scenario before 2030, and hence fossil fuels (especially natural gas) are likely to continue being the predominant energy source in the Basque Country. Secondly, the characteristics of the territory limit the potential of RES.

- Despite the 246 km of coastline, the deep seabed at a short distance from the coast is not well suited to offshore wind farms. Offshore wind power in this region would require floating platforms, a technology which is still at a pilot phase.
- Solar thermoelectric technology is still in a phase which does not allow it to be installed in sites with few hours of insolation and low direct irradiation, as in the Basque Country.
- The potential of geothermal energy is limited low-temperature level, which makes it unfit for power generation with today's technology, although it can be used for space heating of buildings and for industrial processes.
- Wave energy seems a suitable solution, but until this technology reaches a commercial development phase, implementation will be limited. The only plant currently operating in the Basque Country is at Mutriku, with a capacity of 300 kW [Basque Government, 2016].

The share of renewable electricity in the region is expected to increase from the 6.5 % (2014) to 19 % in 2030, mainly thanks to PV and wind energy [Basque Government, 2016]. The Spanish Wind Energy Association expects that 5 G€ will be invested in wind energy in Spain by 2020 [Villalobos, 2018].

In a longer-term perspective, targets are: no use of oil for energy purposes by 2050 (requiring a structural change in the transport system), reduction of GHG emissions by at least 80 % compared to 2005, 40 % contribution of RES to the final energy consumption [Basque Government, 2016].

2.6.5. Potential of the CHEST System

Despite being bigger than Ispaster, Lekeitio is a relatively small town, so the same considerations on the effect of economies of scale mentioned in Section 2.3.5 for Ispaster would likely be valid also in this case to some extent. These considerations are not repeated here, but the reader should refer to Section 2.3.5.

Additionally, based on the project information currently available, energy from renewable sources is not planned to cover the demand, so little amounts of excess heat/electricity can be expected. Furthermore, if considering only the amount of fluctuating renewable electricity, this is limited to the PV production, which is expected to be just 5 % of the demand in the current project phase.

Considering the wider region of the Basque Country instead of the town of Lekeitio, both the current boundary conditions of the electric system and the developments expected for the medium-term future do not seem to indicate this location as the most suitable for implementing a CHEST system. Given the low share of fluctuating renewable electricity (4.2 % of the demand in 2014), its moderate development expected in the near future and the presence of hydroelectric plants, an electricity storage technology such as the CHEST system seems to have a lower priority compared to the support and development of PV and wind electricity production.

The situation could however change completely, if the investigated developments of Lekeitio project, such as exploitation of wind and wave energy, were also to be implemented, so increasing the amount of fluctuating renewable electricity available.

3. Uncompleted case studies

3.1. Case Study #6: Strasbourg, France

The biomass CHP plant located in the Port of Strasburg city produces electricity (10 MW-el) and heat (28 MW-th) that is supplied through the municipal DH network (140 GWh of annual heat consumption). The electricity production releases high amounts of low temperature heat, this is currently wasted (at 30-40 °C, cooled down in cooling towers) and finding a solution for the use of the large amounts of heat that are wasted at present is one of the main concerns of public authorities. ES, the local operator of the power grid, is as well the owner of the biomass CHP plant. The DH infrastructure is public and is managed by public-private partnership through a long-term concession (25 years).

The CHEST system could use the low temperature heat of the CHP plant that is currently wasted. Produced heat (to be used for the DH network) may be also used for the industrial area located near the CHP plant which has relevant heat demand (low temperature process heat). The CHEST system could provide to the plant operator a powerful energy storage and management system to efficiently manage the electricity and heat flows, while increasing energy efficiency and provide flexibility services to the grid.

Additionally, the city of Strasbourg may provide an interesting overall framework for analyzing the potential of the CHEST system at the city level as renewable energy storage and management system. The municipality of Strasbourg is very active in the implementation of renewables (biomass heat and CHP plants already in operation, three new plants planned for deep geothermal for electricity and heat production, solar PV plant under study which may be soon implemented).

References

[Aalborg Forsyning, 2015]. Aalborg Forsyning, Varme. *Strategiplanlægning 2016-2019* (Strategy Planning 2016-2019, in Danish). 2015. Retrieved 12/06/2018 from https://aalborgforsyning.dk/media/407472/strategiplan-2016-19-aalborg-forsyning-varme.pdf.

[Aalborg Varme, 2016]. Aalborg Varme A/S. *Årsrapport 2016* (Annual report 2016, in Danish). 2017. Retrived 12/06/2018 from https://aalborgforsyning.dk/media/769261/aalborg-varme.pdf.

[AGFV, 2016]. Arbeitsgemeinschaft Fernwärme: *AGFW-Hauptbericht 2016* (2016 main report of the German association for efficiency with heat, cold and CHP, in German). 2018. Retrieved 01/09/2018 from https://www.agfw.de/zahlen-und-statistiken/agfw-hauptbericht/

[Alpha Ventus, 2018]. Deutsche Offshore-Testfeld und Infrastruktur GmbH & Co. KG: General and technical information about the wind farm Alpha Ventus. 2018. Retrieved 01/09/2018 from https://www.alpha-ventus.de/ueberblick/

[AMB, 2018]. Area Metropolitana de Barcelona. *Energy*. 2018. Retrieved 21/08/2018 from www.amb.cat/es/web/territori/infraestructures-metropolitanes/sobre-les-infraestructures/energia.

[Baden-Württemberg, 2018]. Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg. *Energieeffiziente Wärmenetze* (Funding program for energy efficient heating networks, in German). 2018. Retrieved 01/09/2018 from https://um.baden-wuerttemberg.de/de/energie/informieren-beraten-foerdern/foerdermoeglichkeiten/energieeffiziente-waermenetze/.

[Barcelona Municipality, 2018]. Barcelona Municipality. *Statistics – economic indicators 2016*. 2018. Retrieved 21/08/2018 from www.bcn.cat/estadistica/castella/dades/anuari/cap11/C1101010.htm.

[Basque Government, 2015]. Basque Government. *Climate Change Strategy of the Basque Country to 2050*. 2015. Retrieved 07/06/2018 from www.ingurumena.ejgv.euskadi.eus/contenidos/informacion/klima_2050/en_def/adjuntos/KLIMA2050_en.pdf.

[Basque Government, 2016]. Basque Government. *Basque Energy Strategy 2030*. 2016. Retrieved 07/06/2018 from www.eve.eus/EVE/media/EVE/pdf/3E/EVE-3E2030-Ingles.pdf.

[Bestenlehner, 2014]. Bestenlehner, D., Drück, H., Stübler, A. *Energetisches Einsparpotential eines kalten Nahwärmenetzes zur Wärmeversorgung eines Stadtquartiers im Vergleich zu einem konventionellen Nahwärmenetz* (Energy saving potential of a cold district heating system compared to a conventional district heating system, in German). 2014. Symposium Thermische Solarenergie, May 7-9, 2014, Bad Staffelstein, Germany.

[Breitschopf, 2016]. Breitschopf, B., Wachsmuth, J., Schubert, T., Schleich, J. *Prices and costs of EU energy*. 2016. Retrieved 09/10/2018 from https://ec.europa.eu/energy/sites/ener/files/documents/annex2_ecofys2016.pdf.

[Bundesministerium der Justiz, 2015a]. *Gesetz für den Ausbau erneuerbarer Energien* (German Renewable Energy Sources Act, in German). 2015. Retrieved 01/09/2018 from www.gesetze-im-internet.de/eeg_2014/.

[Bundesministerium der Justiz, 2015b]. *Gesetz zur Förderung Erneuerbarer Energien im Wärmebereich* (German Act for the support of renewable energies in the heat sector, in German). 2015. Retrieved 01/09/2018 from www.gesetze-im-internet.de/eew_rmeg/.

[Bundesministerium der Justiz, 2017]. *Gesetz für die Erhaltung, die Modernisierung und den Ausbau der Kraft-Wärme-Kopplung* (German Act for the conservation, modernization and expansion of combined heat and power, in German). 2017. Retrieved 01/09/2018 from www.gesetze-im-internet.de/kwkg_2016/.

[Bundesministerium für Umwelt, 2017]. Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB). *Klimaschutzplan 2050. Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung* (Climate Action Plan 2050, in German). 2017. Retrieved 01/09/2018 from www.bmu.de/publikation/klimaschutzplan-2050-klimaschutzpolitische-grundsaetze-und-ziele-der-bundesregierung/

[Bundesministerium für Wirtschaft, 2018a]. Bundesministerium für Wirtschaft und Energie, Informationsportal Erneuerbare Energien. *Wärme aus Erneuerbaren: das Marktanreizprogramm für Privatpersonen, Unternehmen und Kommunen* (market incentive program for private households, companies and municipalities, in German). 2018. Retrieved 01/09/2018 from www.erneuerbare-energien.de/EE/Navigation/DE/Foerderung/Marktanreizprogramm/marktanreizprogramm.html.

[Bundesministerium für Wirtschaft, 2018b]. Bundesministerium für Wirtschaft und Energie. *Zeitreihen zur Entwicklung der Erneuerbaren Energien in Deutschland* (Figures for the development of renewable energy sources in Germany, in German). 2018. Retrieved 01/09/2018 from www.erneuerbare-energien.de/EE/Navigation/DE/Service/Erneuerbare_Energien_in_Zahlen/Zeitreihen/zeitreihen.html.

[BWE, 2018]. Bundesverband WindEnergie. Information about offshore wind energy by the German Association for wind energy. 2018. Retrieved 01/09/2018 from www.wind-energie.de/themen/anlagentechnik/offshore/.

[Cluster Energia, 2017]. Cluster Energia. *Offshore wind energy - Basque Country*. 2017. Retrieved 07/06/2018 from www.clusterenergia.com/offshore-wind-basque-country-3.

[DEA, 2017]. Danish Energy Agency. *Regulation and Planning of District Heating in Denmark*. 2017. Retrieved 12/06/2018 from https://ens.dk/sites/ens.dk/files/Globalcooperation/regulation_and_planning_of_district_heating_in_denmark.pdf.

[Degenhart, 2017]. Degenhart, H. *Wärmenetze und Erneuerbare Energie. Stand, Entwicklung und Finanzierung in Deutschland* (Status, development and financing of heating networks and renewable energy, in German). 2017. Energieforum Lüneburg, Sept 27, 2017, Lüneburg, Germany.

[Districlima, 2018]. Districlima website. 2018. Retrieved 21/08/2018 from www.districlima.com.

[Emden, 2018]. Personal communication with employees of the municipality and of the energy provider in Emden. 2018.

[Emden, 2018]. Stadt Emden. *Masterplan 100% Klimaschutz für Emden* (Status and action plan for energy and climate protection in Emden, in German). 2017. Retrieved 07/05/2018 from www.emden.de/rathaus/verwaltung/fb-300-stadtentwicklung-und-wirtschaftsfoerderung/fd-362-umwelt/klimaschutz-in-emden/masterplanklimaschutzmanagement/.

[Energi Data Service, 2018]. Energi Data Service. *Electricity Balance Data* and *Nordpool Market Data*. 2018. Retrieved 07/06/2018 from www.energidataservice.dk/en/dataset.

[Energy Transition Platform, 2016]. Energy Transition Platform. *Partner region profile – Basque Country: Socio-economic facts*. 2016. Retrieved from 07/06/2018 from www.theclimategroup.org/sites/default/files/ etp_partnerprofile_basquecountry.pdf.

[Eurostat, 2018]. Eurostat. *Electricity prices for household consumers (taxes included) second half 2017 (EUR per kWh)*. 2018. Retrieved 07/06/2018 from http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics#Electricity_prices_for_non-household_consumers.

[EZE Barrizar, 2017a]. EZE Barrizar. *Suministro de agua caliente, calefacción y electricidad mediante energías renovables con eficencia energética* (Supply of hot water, heating and electricity through renewable energy with energy efficiency, in Spanish). 2017. Retrieved 07/06/2018 from www.ehu.eus/documents/1294053/3185002/I%C3%B1aki+Gaztelu.

[EZE Barrizar, 2017b]. EZE Barrizar. *Estudio previo para la instalación de una planta de cogeneración con biomasa y energía solar* (A pre-study for the installation of a cogeneration plant with biomass and solar energy, in Spanish). 2017. Retrieved 07/06/2018 from http://barrizar.com/wp-content/uploads/2016/09/Estudio-Previo-MADERAS-de-LEKEITIO-2017.pdf.

[Fraunhofer ISE, 2018]. Fraunhofer Institut für Solare Energiesystem. Electricity production and spot electricity market prices for Germany. 2018. Retrieved 01/09/2018 from www.energy-charts.de/price_de.htm.

[Gohl, 2017]. Gohl, N., Bestenlehner, D., Drück, H. *Extension of Germany´s largest solar district heating system with seasonal thermal energy storage*. 2017. Solar World Congress / Solar Heating and Cooling Conference, Oct 29-Nov 2, 2017, Abu Dhabi, UAE.

[Guascor, 2009]. Guascor Bioenergía. Generación distribuida mediante gasificación de biomasa (Distributed generation through gasification of biomass, in Spanish). 2009. Retrieved 07/06/2018 from www.fundacionenergia.es/pdfs/0911%20BIOMASA/Txema%20Avelino.pdf.

[ICAEN, 2018]. Instituto Catalán de Energía. *Balance de energía eléctrica de Cataluña* (Electricity balance of Catalonia, in Spanish). 2018. Retrieved 21/08/2018 from http://icaen.gencat.cat/es/energia/estadistiques/resultats/anuals/balanc_energia.

[IEA, 2016]. International Energy Agency. *Spain Energy Report*. 2016. Retrieved 01/10/2018 from www.iea.org/publications/freepublications/publication/IDR_Spain2015.pdf.

[IEA, 2017]. International Energy Agency. *Energy Policies of IEA Countries: Denmark*. 2017. Retrieved 07/06/2018 from www.regeringen.dk/media/4447/energi-rapport-iea.pdf.

[IREN, 2017]. IREN. *Teleriscaldamento Iren: 900 km di rete, 850 mila abitanti serviti ed un piano al 2021 di ulteriore crescita infrastrutturale*. 2017. Retrieved 26/06/2018 from www.gruppoiren.it/documents/21402/153586/17_05_2017CONVEGNO.pdf/e3008464-0f62-43fe-81c8-55728eba95af.

[IREN, 2018]. IREN. *Produzione* (Production, in Italian). 2018. Retrieved from IREN's website 26/06/2018 from www.gruppoiren.it/production.

[Jarre, 2016]. Jarre, M., Noussan, M., Poggio, A. *Operational analysis of natural gas combined cycle CHP plants: Energy performance and pollutant emissions*. Applied Thermal Engineering, 100, pp. 304–314, 2016. https://doi.org/10.1016/j.applthermaleng.2016.02.040.

[La Voce, 2018]. La Voce Editorial Staff. *Torino, Viaggio nel termovalorizzatore* (Turin, Visit to the waste-to-energy plant, in Italian). La Voce 23/06/2018. 2018. Retrieved 26/06/2018 from www.giornalelavoce.it/torino-viaggio-nel-termovalorizzatore-308684.

[López Prol, 2017]. López Prol, J., & Steininger, K. W. *Photovoltaic self-consumption regulation in Spain: Profitability analysis and alternative regulation schemes*. 2017. Energy Policy, 108, 742–754. https://doi.org/10.1016/j.enpol.2017.06.019.

[Norden, 2018]. Personal communication with employees of the municipality and of the energy providers in Norden. 2018.

[Pirner, 2018] Pirner, K. *New Spanish Government to Prioritise Climate Change Policy*. 2018. Retrieved 22/08/2018 from www.southeusummit.com/europe/spain/new-spanish-government-to-prioritise-climate-change-policy.

[RAVE, 2018]. RAVE – Research at Alpha Ventus. 2018. Retrieved 01/09/2018 from www.rave-offshore.de/de/start.html.

[Ravina, 2018]. Ravina, M., Panepinto, D., Zanetti, M. *District heating system: evaluation of environmental and economic aspects*. International Journal of Environmental Impacts, 1, pp. 420-432, 2018. https://doi.org/10.2495/EI-V1-N4-420-432.

[Recknagel, 2018]. Recknagel online. *Wärmenetze: Potenziale, Technologien und Rahmenbedingungen* (Potentials, technologies and boundary conditions of heating networks, in German). 2018. Retrieved 01/09/2018 from www.recknagel-online.de/aktuell/energiewende/30-05-2018-waermenetze-potenziale-technologien-und-rahmenbedingungen/.

[REE, 2017]. Red Eléctrica de España. *Informe del Sistema Eléctrico Español* (Reprt on the Spanish Electric System, in Spanish). 2017. Retrieved 01/10/2018 from www.ree.es/es/estadisticas-del-sistema-electrico-espanol/informe-anual/informe-del-sistema-electrico-espanol-2017.

[REE, 2018]. Red Eléctrica de España. *Series estadísticas por comunidades autónomas* (Statistics per autonomous community, in Spanish). 2018. Retrieved 21/08/2018 from www.ree.es/es/estadisticas-del-sistema-electrico-espanol/series-estadisticas/series-estadisticas-por-comunidades-autonomas.

[Rühling, 2018]. Rühling, K. *Thementisch Marktchancen Fernwärme: Herausforderungen und Lösungsansätze zur dezentralen Einbindung von regenerativen Energien* (Discussion table on the challenges and solutions for the use of renewable energies in district heating systems, in German). 2018. Symposium Solarthermie, June 14, 2018, Bad Staffelstein, Germany.

[S&P, 2018]. S&P Global Ratings. *Spain Ends Subsidies on Renewables*. 2018. Retrieved 07/06/2018 from www.sustainablecitynetwork.com/topic_channels/energy/article_f9733d52-0cee-11e8-b075-bf49d49e8cc9.html.

[Serrano, 2018]. Serrano, D. *A consolidated DHC: A smart solution for a sustainable environment*. 2018. Retrieved 21/08/2018 from www.districlima.com/en/downloads.

[Statistisches Bundesamt, 2018]. Statistisches Bundeamt. *Daten zur Energiepreisentwicklung – Lange Reihen* (Statistical data about the German development of energy prices, in German). 2018. Retrieved 01/09/2018 from www.destatis.de/DE/Publikationen/Thematisch/Preise/Energiepreise/Energiepreisentwicklung.html.

[TERNA, 2018a]. TERNA. *Dati statistici – Consumi* (Statistical data - consumption, in Italian). 2018. Retrieved 26/06/2018 from www.terna.it/it-it/sistemaelettrico/statisticheeprevisioni/datistatistici.aspx.

[TERNA, 2018b]. TERNA. *Dati statistici – Carichi* (Statistical data - load, in Italian). 2018. Retrieved 26/06/2018 from www.terna.it/it-it/sistemaelettrico/statisticheeprevisioni/datistatistici.aspx.

[TERSA, 2018]. TERSA. *Sant Adrià de Besòs Waste-to-Energy Plant*. Retrieved 21/08/2018 from www.tersa.cat/en/sant-adrià-de-besòs-waste-to-energy-plant_2172.

[Tjaden, 2015]. Tjaden, T., Bergner, J., Weniger, J., Quaschning, V. *Repräsentative elektrische Lastprofile für Einfamilienhäuser in Deutschland auf 1-sekündiger Datenbasis* (Representative electrical load profiles for single-family houses in Germany on 1-second data basis, in German). 2015. HTW Berlin – University of Applied Sciences.

[TRM, 2018]. Website of TRM company (TRM - Trattamento Rifiuti Metropolitani, translated in English as Treatment of Metropolitan Waste). 2018. Retrieved on 02/07/2018 from http://trm.to.it.

[Villalobos, 2018]. Villalobos, A. *Spain's Bilbao fights to lead European wind power sector*. 2018. Retrieved 07/06/2018 from https://phys.org/news/2018-05-spain-bilbao-european-power-sector.html.

[Vortex, 2018]. Vortex Bladeless. Web site. Retrieved 07/06/2018 from https://vortexbladeless.com.

[Wikipedia, 2018]. Wikipedia. List of offshore wind farms. 2018. Retrieved 01/09/2018 from https://en.wikipedia.org/wiki/List_of_offshore_wind_farms.