CHESTER

Compressed Heat Energy
Storage for Energy
from Renewable sources

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

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

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Authors		Federico Bava, Dadi Sveinbjörnsson (PlanEnergi)	
Reviewed by		Eduardo Zabala, Silvia Alonso, Carol Pascual	
Approved by		Eduardo Zabala	
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Glossary, Abbreviations and Acronyms

CAD	Computer-Aided Drawing
CHEST	Compressed Heat Energy STorage
CHP	Combined Heat and Power
DH	District Heating
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
ORC	Organic Rankine Cycle
SCADA	Supervisory Control And Data Acquisition
TSO	Transmission System Operator
TES	Thermal Energy Storage
TTES	Tank Thermal Energy Storage

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, 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.

CHESTER has seven cases studies. This D2.1 version has been developed based on the tree case studies whose information was supplied before month 3, as foreseen in the DoA:

- Aalborg (Denmark): large DH network,
- Ispaster (Spain): small DH network and micro electrical grid,
- Lekeitio (Spain): DH network (still in design phase).

A new version of D2.1 will be prepared and delivered before end September 2018, including information of the other 4 case studies, as well as the new findings or approaches that can arise:

- Turin (Italy): large DH network,
- Barcelona (Spain): DH&C network,
- Alpha Ventus (Germany): offshore wind farm,
- Strasbourg (France): large DH network.

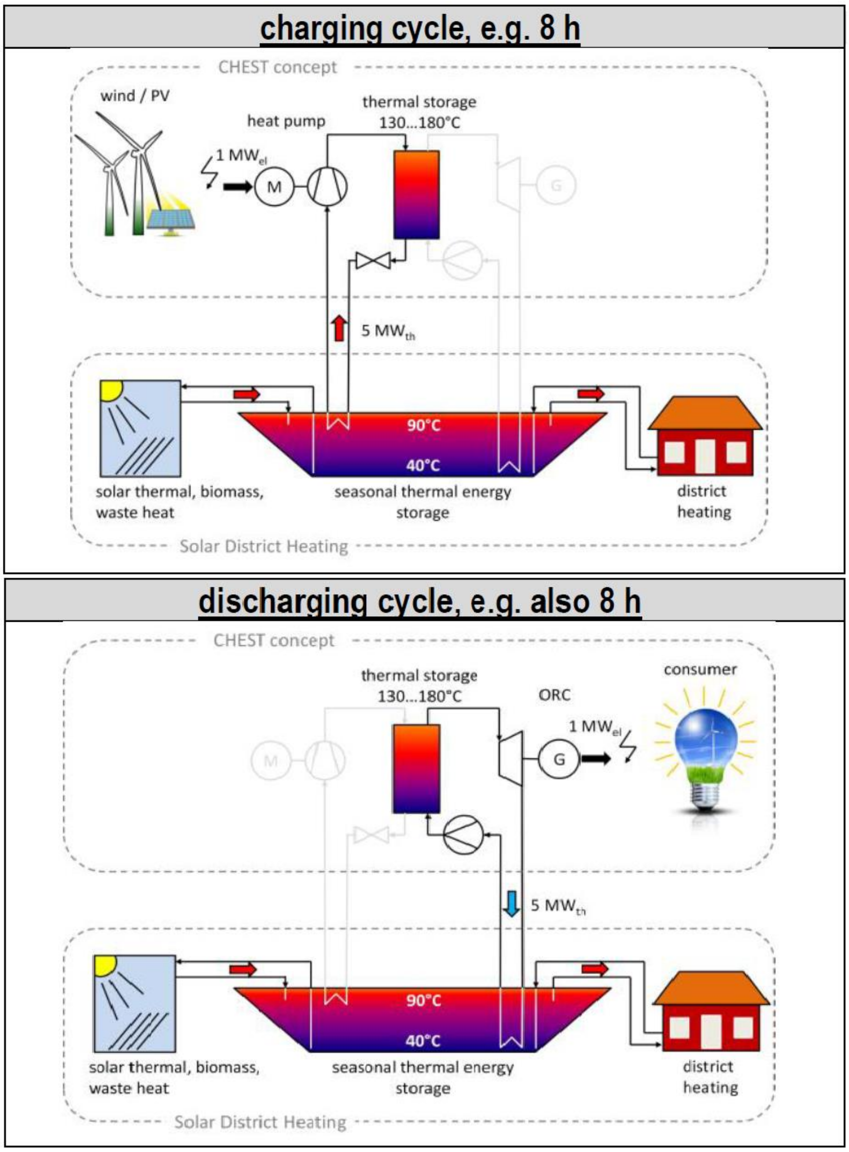

Figure 1: Principle scheme of a CHEST system integrated in DH system equipped with water pit storage.

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 send 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,
        - annual 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,
    - annual 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 seven sections one per case study. Currently the completed sections regard the case studies of Aalborg (Section 2.1), Ispaster (Section 2.2) and Lekeitio (Section 2.3).

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 remaining uncompleted case studies are listed in Section 3 (Annex 1) and will be treated in detail in a second version of this deliverable, which is expected to be completed by end September 2018.

2. Case Studies

2.1. 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.

2.1.1. Energy Demand

District Heating Demand

Some key parameters of Aalborg's DH network are shown in Table 1. 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 1: 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.

2.1.2. 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 2. The different DH producers are shown in terms of production capacity, yearly energy output and operation priority (with 1 being the highest priority and 9 being the lowest priority). The electricity generation units are listed in Table 3.

The DH producers in Table 2 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.

Table 2: 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

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 sometime 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.

Table 3: 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 4. 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 4: Key figures for the existing and planned thermal energy storages 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

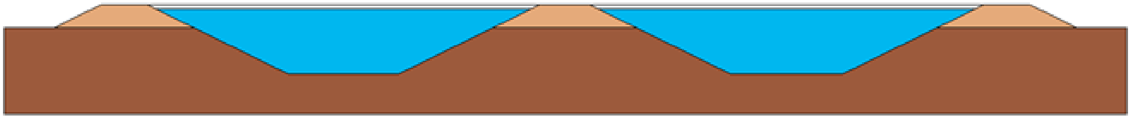

Figure 2: A schematic representation of the cross-section of the planned 1,000,000 m^3 PTES storage (Figure by PlanEnergi).

In addition to the existing TTES storages, 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 requirement for such a PTES storage (two squares with a volume of 500,000 m^3 each) is approximately 11 hectares. A schematic visualization of a cross-section of the double PTES is shown in Figure 2. The side walls are dimensioned for soil-balance, i.e. that precisely all excavated soil is used for the formation of the side walls (no soil must be delivered or disposed of during the building of the storage). The white lines on the water surface in Figure 2 represent the lid of the storages, which is insulated and floats on the water.

2.1.3. 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 taxes rates for fuels and excess heat for DH purposes are shown in Table 5.

Table 5: 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 connects 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 6. 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 5).

Table 6: Tax rates for electricity depending on what it is used for. Energy tax, transmission and system tariff and PSO values for 2018.

Energy source	Units	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

2.1.4. 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 renewable energy 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 renewable energy 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 renewable energy 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 renewable sources, i.e. wind power, photovoltaics 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).

2.1.5. 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 2), 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.

2.2. 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 renewable energy.

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].

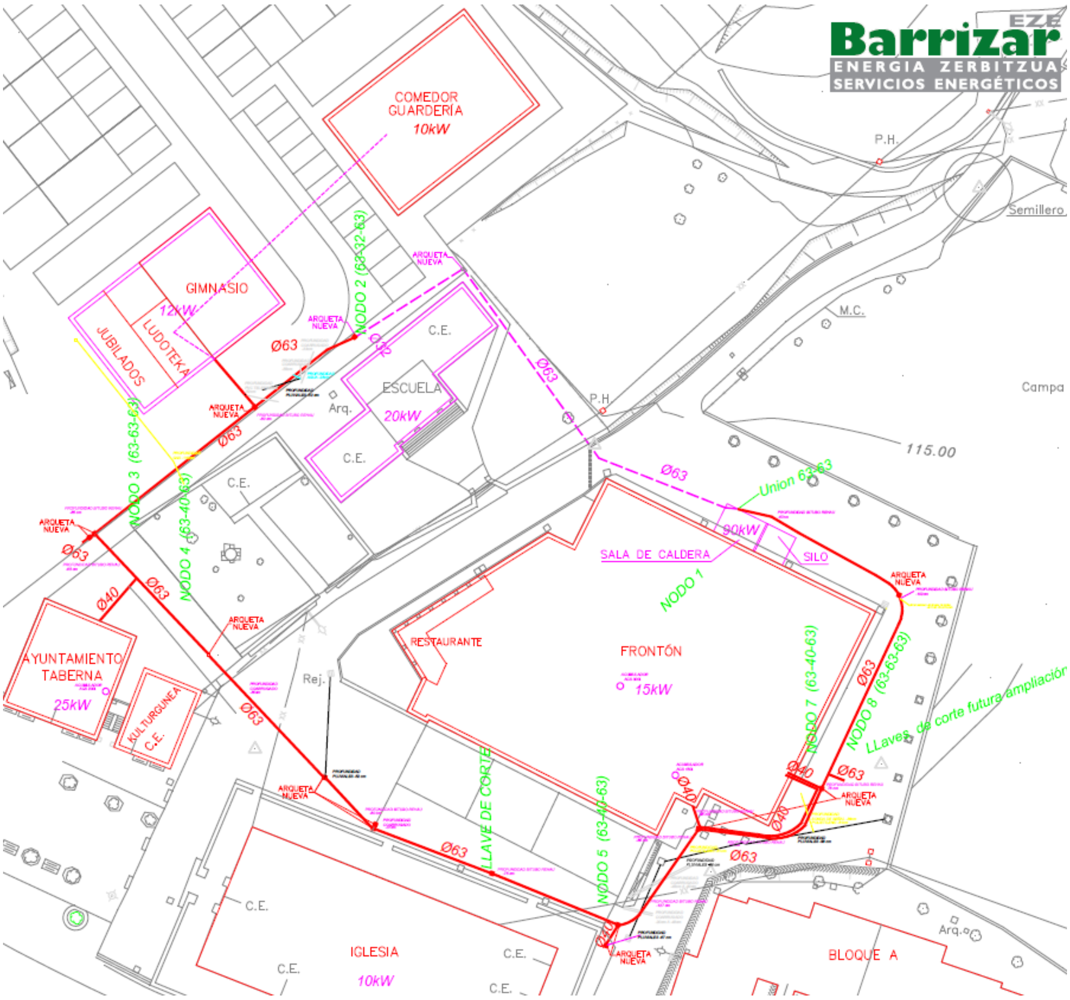

Figure 3: CAD representation of the DH network. The DH ring is represented by the thick red lines and by the dashed pink lines.

2.2.1. Energy Demand

District Heating Demand

A small DH network (in a shape of a ring, see Figure 3) was installed between 2014 and 2015, to supply heat to 11 public buildings. These were the local school (*Escuela* in Figure 3), 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 4.

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.

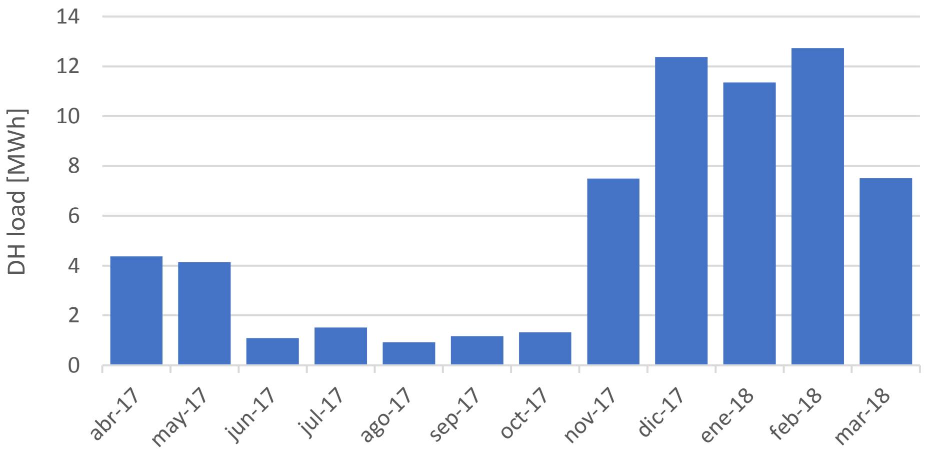

Figure 4: Monthly load of the DH network in the period April 2017-March 2018.

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 3);
- 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 2.2.2). 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.

2.2.2. Energy Supply

District Heating Supply

A principle scheme of the DH network is shown in Figure 5. The scheme refers to the system before the installation of the solar thermal collectors in 2016. 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 3). The wood chips fed to the boiler derive from biomass collected in the forests around Ispaster. With a lower calorific value of 3.5-4.4 kWh/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 located in the basement of the play center (*Storage tank* in Figure 5). The tank was not connected yet at the time of writing the report (June 2018), but it should be by the end of the year.

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.

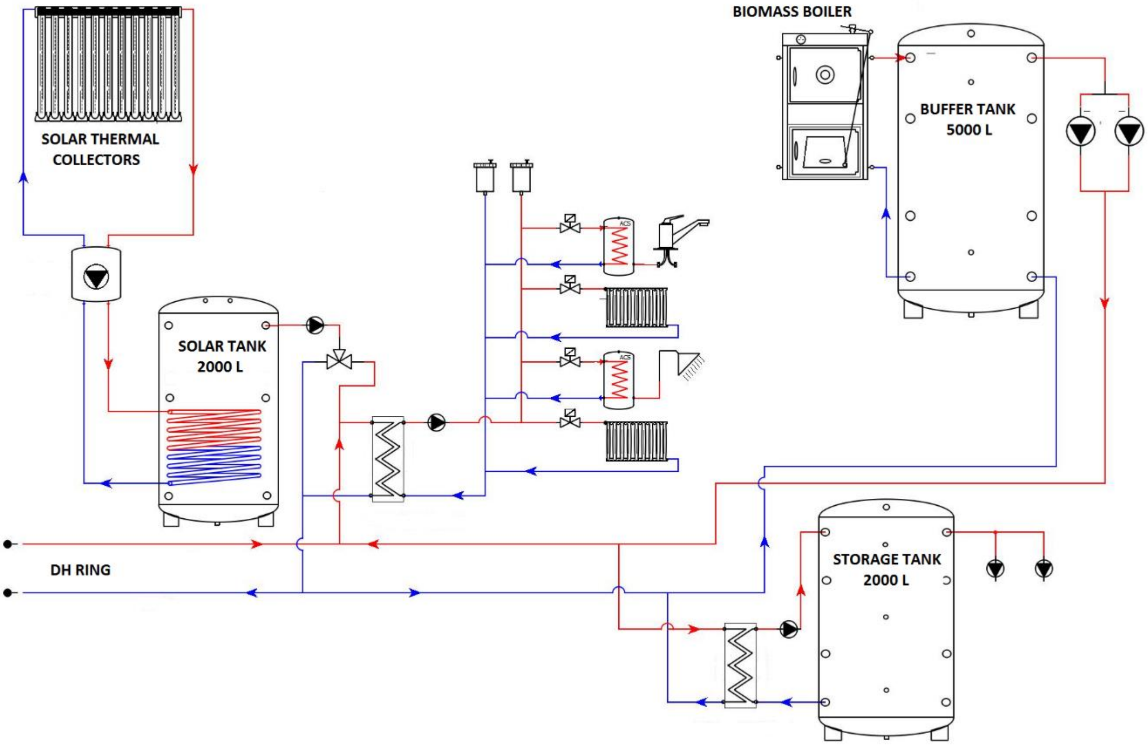

Figure 5: Principle scheme of DH network, supply and demand side.

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 2.2.1).

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.

2.2.3. Existing Boundary Conditions

It should be pointed out that Ispaster —with its high share of renewable energy, 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 2.3.3 (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 renewable energy sources for electricity production. Especially PV boomed between 2007 and 2008, with installed capacity increasing from 637 MW to 3355 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.

According to the law currently regulating the electricity sector [BOE, 2013], all consumers which perform any kind of self-consumption must contribute to the costs of the electrical network for self-consumed electricity, whenever the generation and/or consumption facility is totally or partially connected to the network. Additionally, for relatively small PV installations it is very complex from the bureaucratic point of view to be entitled to sell electricity to the DSO network. So, in most cases the excess electricity is either given for free or curtailed.

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: solar 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 (RAB) 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.

2.2.4. Future Perspective

The DH network in Ispaster is expected to expand in the future, so to supply other public buildings and also 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.

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 2.3.4 (Lekeitio case).

At a national level, the radical shift from a fixed feed-in tariff to fluctuating electricity prices significantly has increased market exposure for renewable energy projects. This has added more complexity for projects financed through project finance structures —i.e. projects whose investment is secured based on the projected cash flows of the project itself—, given their long-term debt tenors. 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 market conditions are expected to continue in the coming years.

2.2.5. Potential of the CHEST System

The size of Ispaster entails that a potential CHEST system would be small. The investment cost per unit volume of the HT-TES would likely be lower for large sizes because of the economies of scale. Additionally, the energy content of the storage is proportional to its volume, while the heat losses are proportional to the area of external surface of the storage, which means that they are proportional to the volume at the power of 2/3. This entails that a bigger storage would be more efficient from an energy point of view, because the increase in energy content would outweigh the increase in thermal losses. A larger installation is expected to entail also a lower specific cost per unit power of the ORC and HP components due to the economies of scale. However, the scalability of these components and the effect on the investment cost are not known at this early stage, but they will be addressed later on in other deliverables of the CHESTER project.

On the other hand, the implementation of a CHEST system in Ispaster could be investigated as a valid alternative to the use of batteries as a means 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. Additionally, the simultaneous presence of a DH network and buffer tanks could represent both heat source and a heat sink for the CHEST system, depending on the season and the electricity/heat demand. For example, during the daytime in summer, the excess of electricity produced by the PV panels 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. The HT-TES could be later discharged (e.g. at night or during cloudy days), producing electricity through the ORC system. 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 DH network efficiency.

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 level 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.

2.3. 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 2.2), 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].

2.3.1. 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.

2.3.2. 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 6. The result of this gasification process is a syngas with low calorific value (about 5 MJ/m3), 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.

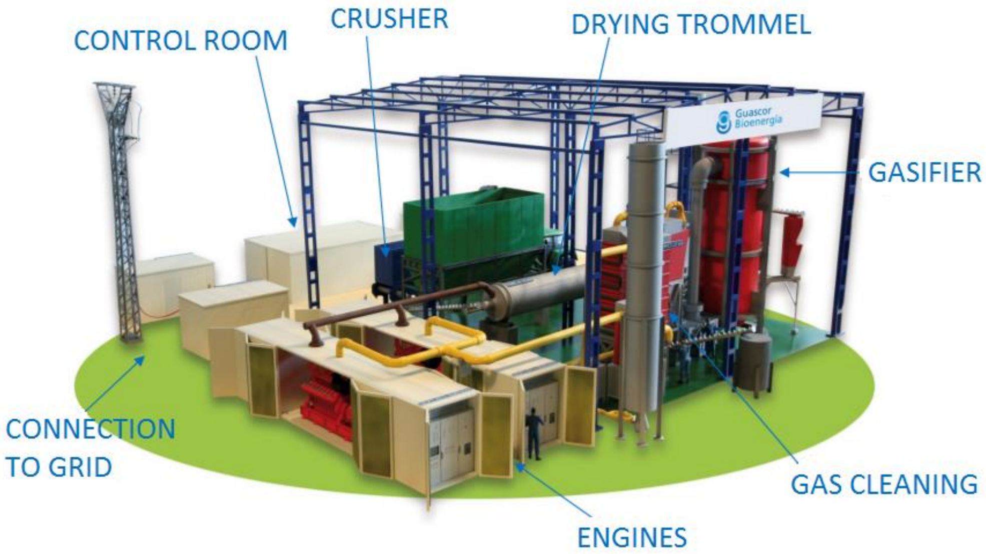

Figure 6: Scheme of the Guascor gasification+CHP plant [Guascor, 2009].

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 7.

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.

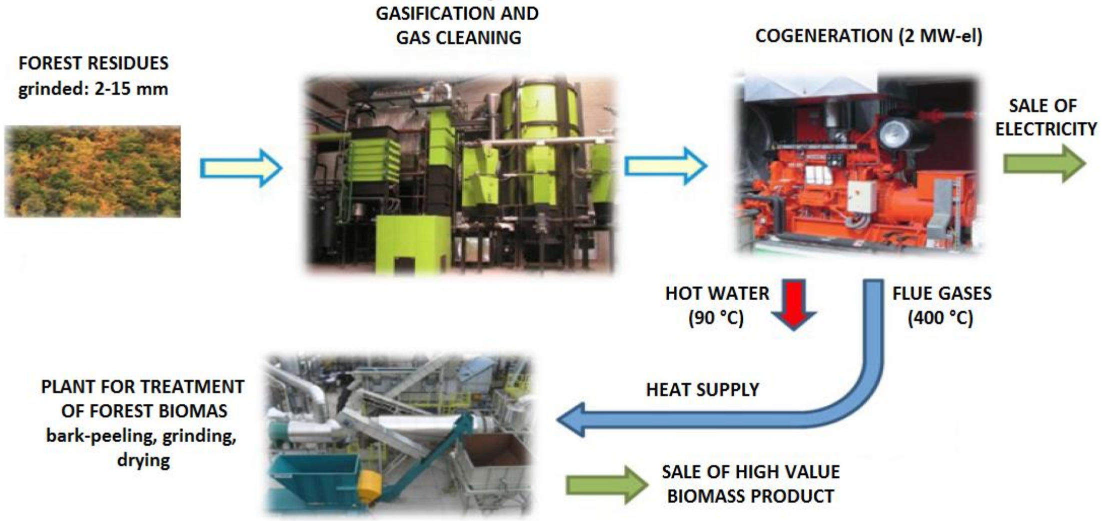

Figure 7: Principle scheme of the biomass cycle in Lekeitio project [Barrizar, 2017b].

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 8).

Solar thermal collectors —most likely with the same vacuum tube + CPC technology as in Ispaster (see Section 2.2) — 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 8: Potential roof area for PVT installation in Lekeitio [Barrizar 2017b].

2.3.3. 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, renewable energy 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 renewable energy sources (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 a more comprehensive description of the current situation of the energy sector in Spain, the reader should refer to Section 2.2.3.

2.3.4. 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 renewable energy 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 renewable energy 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 renewable energy production.

- 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 renewable energy to the final energy consumption [Basque Government, 2016].

2.3.5. 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 2.2.5 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 2.2.5.

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 solar 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. Annex 1: Case studies to be developed by 30/09/2018

3.1. Case Study #1: Turin, Italy

- General description of the system

3.1.1. Energy Demand

District Heating Demand

- Network information: lengths, temperatures, no. of consumers, type of net
- Load: local yearly consumption, seasonal/daily profiles, supply/return temperature + (eventually) seasonal temperature profiles

Electricity Demand

- Load: yearly amount of local consumption, load profiles

3.1.2. Energy Supply

District Heating and Electricity Supply

[divided in two subheadings if CHP is not present]

- CHPs: installed capacities/yearly outputs, profiles, operation, regulation and control principles
- Boilers: installed capacities/yearly outputs, profiles, operation, regulation and control principles
- Eventually, other thermal or electrical generation units?

Energy Storage

- Thermal storage: type (water tanks, others), temperatures, volumes, control strategy

3.1.3. Existing Boundary Conditions

- Electricity tariffs, market, regulation methodology
- Any other relevant boundary condition (legislation, technical, etc.)

3.1.4. Future Perspective

- Expected boundary conditions for 2030 and 2050: such as electric tariffs, electric markets, future regulation, future legislation, development of DH

3.1.5. Potential of the CHEST System

- User requirements
- Potential interaction between CHEST system and existing system (qualitative description)

3.2. Case Study #4: Barcelona, Spain

- General description of the system

3.2.1. Energy Consumption

District Heating Consumption

- Network information: lengths, temperatures, no. of consumers, type of net
- Load: local yearly consumption, seasonal/daily profiles, supply/return temperature + (eventually) seasonal temperature profiles

Electricity Consumption

- Load: yearly amount of local consumption, load profiles

3.2.2. Energy Supply

District heating and Electricity Supply

[divided in two subheadings if CHP is not present]

- CHPs: installed capacities/yearly outputs, profiles, operation, regulation and control principles
- Boilers: installed capacities/yearly outputs, profiles, operation, regulation and control principles
- Eventually, other thermal or electrical generation units?

Energy Storage

- Thermal storage: type (water tanks, others), temperatures, volumes, control strategy

3.2.3. Existing Boundary Conditions

- Electricity tariffs, market, regulation methodology
- Any other relevant boundary condition (legislation, technical, etc.)

3.2.4. Future Perspective

- Expected boundary conditions for 2030 and 2050: such as electric tariffs, electric markets, future regulation, future legislation, development of DH

3.2.5. Potential of the CHEST System

- User requirements
- Potential interaction between CHEST system and existing system (qualitative description)

3.3. Case Study #5: Alpha Ventus Wind Park, Germany

- General description of the system

3.3.1. Energy Consumption

District Heating Consumption

- Network information: lengths, temperatures, no. of consumers, type of net
- Load: local yearly consumption, seasonal/daily profiles, supply/return temperature + (eventually) seasonal temperature profiles

Electricity Consumption

- Load: yearly amount of local consumption, load profiles

3.3.2. Energy Supply

District heating and Electricity Supply

[divided in two subheadings if CHP is not present]

- CHPs: installed capacities/yearly outputs, profiles, operation, regulation and control principles
- Boilers: installed capacities/yearly outputs, profiles, operation, regulation and control principles
- Eventually, other thermal or electrical generation units?

Energy Storage

- Thermal storage: type (water tanks, others), temperatures, volumes, control strategy

3.3.3. Existing Boundary Conditions

- Electricity tariffs, market, regulation methodology
- Any other relevant boundary condition (legislation, technical, etc.)

3.3.4. Future Perspective

- Expected boundary conditions for 2030 and 2050: such as electric tariffs, electric markets, future regulation, future legislation, development of DH

3.3.5. Potential of the CHEST System

- User requirements
- Potential interaction between CHEST system and existing system (qualitative description)

3.4. Case Study #6: Strasbourg, France

- General description of the system

3.4.1. Energy Consumption

District Heating Consumption

- Network information: lengths, temperatures, no. of consumers, type of net
- Load: local yearly consumption, seasonal/daily profiles, supply/return temperature + (eventually) seasonal temperature profiles

Electricity Consumption

- Load: yearly amount of local consumption, load profiles

3.4.2. Energy Supply

District heating and Electricity Supply

[divided in two subheadings if CHP is not present]

- CHPs: installed capacities/yearly outputs, profiles, operation, regulation and control principles
- Boilers: installed capacities/yearly outputs, profiles, operation, regulation and control principles
- Eventually, other thermal or electrical generation units?

Energy Storage

- Thermal storage: type (water tanks, others), temperatures, volumes, control strategy

3.4.3. Existing Boundary Conditions

- Electricity tariffs, market, regulation methodology
- Any other relevant boundary condition (legislation, technical, etc.)

3.4.4. Future Perspective

- Expected boundary conditions for 2030 and 2050: such as electric tariffs, electric markets, future regulation, future legislation, development of DH

3.4.5. Potential of the CHEST System

- User requirements
- Potential interaction between CHEST system and existing system (qualitative description)

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