PITAGORAS Sustainable urban planning with innovative and low energy thermal and power generation from residual and renewable sources

Deliverable 2.16: Publishable report of the two demonstration plants

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LIST OF ABBREVIATIONS

ANN: Artificial Neural Networks.

BFW: Boiler feed water

CHP: Combined Heat and Power.

DH: District Heating.

EAF: Electric Arc Furnace

EMS: Energy Management System.

ESCO: Energy Service Company.

HT: High temperature

HX: Heat Exchanger

LCOE: Levelized Cost of Energy

LT: Low temperature

ORC: Organic Rankine Cycle.

PFD: Process Flow Diagram.

RES: renewable energy sources.

STES: Seasonal Thermal Energy Storage.

WHR: Waste Heat Recovery

WHRU: Waste Heat Recovery Unit.

EXECUTIVE SUMMARY

PITAGORAS (Sustainable urban planning with innovative and low energy thermal and power generation from residual and renewable sources) is a European funding project framed into FP7 – Smart Cities program.

The PITAGORAS project focuses on the efficient integration of city districts with industrial parks through smart thermal grids. Technologies and concepts for low and medium temperature waste heat recovery, considering as well integration with renewable energy sources (RES), and heat (and power) supply to cities are intended to be developed and demonstrated.

The overall objective of the project is to demonstrate a highly replicable, cost-effective and high energy efficiency large scale energy generation system that will allow sustainable urban planning of very low energy city districts. In concrete, the Pitagoras project has worked in the definition of two system concepts.

On the one hand, a waste heat recovery plant has been developed for a stell mill owned by ORI MARTIN and located in Brescia (Italy), to recover the waste heat form the fumes coming from the Electric Arc Furnace (EAF). A 10 MW_{th} Waste Heat recovery Unit has been developed in order to produce saturated steam from the flue gases. The thermal energy produced is stored in a Steam Accumulator, which enables a stable heat and electricity production although the highly discontinuous operation of the EAF. The steam can be used for heat production and supply to the city district heating network by means of steam/water heat exchagners (10MWth) or to feed the ORC unit to produce electricity (1,8MWe), which is the operation strategy followed in summer time. The thermal energy production expected is around 26.500MWh/year and electricity generation of around 4.200MWh/year which will be used for self-consumption. The plant is actually in regular operation since June 2016 and a monitoring campaign is being carried out in order to perform a detailed performance assessment and optimization. The present document comprises a comprehensive description of the developed concept and implemented pilot plant.

On the other hand, the project has worked in a second different system concept based on industrial integration of solar thermal energy in combination with seasonal thermal energy storage (STES) concept, including the possibility of solar heat delivery also to the district heating network. The plant has been planned for a specific site in the city of Kremsmünster (Austria) and in an industrial area of an oil and gas industry. The developed system concept is formed by a solar field of 9377 m^2, which is expected to produce around 4547MWh of useful solar heat per year. The integration of the STES concept allows to maximize the solar yield and to get the high solar net gain of 485kWh/m^2 according to performed simulations. The idea of reconverting an existing oil tank of 60000 m^3 of storage volume (that will not longer be used) into a STES allows to store the surplus solar heat in summer and its use later on in winter months, which significantly increase the solar production capabilities, system performance as well as economics. The challenge has been to develop a reconversion solution that is technically and economically feasible. This report presents the main challenges encountered within the design process of this system, together with a description of the plant and main features of the developed Pitagoras concept.

1. INTRODUCTION

1.1. BASELINE

This report builds on results achieved in the European founded PITAGORAS project in its WP2 “System concept assessment and final design” and comprises the main outputs regarding the design phase of two real scale pilot plants.

One of the pilot plants is located in the city of Brescia (north of Italy) and consists on a waste heat recovery solution to be implemented in the steel mill of ORI MARTIN. The plant will deliver heat to the city district heating (DH) network and will produce electricity based on ORC technology.

The city of Kremsmünster (upper Austria) is the location of the second pilot plant that has been designed within the PITAGORAS project. A large scale solar thermal plant is planned for solar heat supply to an oil and gas industry and additionally to the city DH network. The system concept comprises the idea of rebuilding an empty oil tank at the production facilities of the industrial site in such a way that it could be used as seasonal thermal energy storage (STES) system.

1.2. PURPOSE OF THE DOCUMENT

The aim of this document is providing a comprehensive description of the two real scale pilot plants that have been designed within the PITAGORAS project. Both demonstration plants basis, technical design, optimization process and main challenges encountered are among other issues reported.

In addition this report shows the main results regarding the development of the so called “Energy Management System” (EMS) for the Brescia pilot plant. The EMS aims to optimize the overall system operation based on Artificial Intelligence algorithms in order to minimize the payback of the overall system through the most efficient exploitation of the energy flows.

On the other hand, the main outcomes of the developed study regarding the applicability of the Brescia pilot plant concept are as well reported. The applicability of this concept in other European cities and under different boundary conditions has been analyzed in order to spot the best potential situations for the replicability of the developed concept.

1.3. RELATIONS TO OTHER ACTIVITIES AND FURTHER CONTEXT

The present document is focused on the two pilot plants that have been designed and planned within the PITAGORAS project and aims at providing information that may be interesting regarding the conceptual design phase. It is worth to mention the framework and follow-up activities in regards to the planned pilot plants.

The pilot plant in Brescia has been already implemented and comissioned and it is currently under regular operation (since June 2016). The pilot plant performance is being monitored in detail. Further results will be reported accordingly during 2016-2017.

The situation regarding the Kremsmünster pilot plant is considerably different. Although the oil and gas company in which the pilot plant was going to be built confirmed their interest on the solar project and the main aspects on the heat delivery contract were in fact agreed between the ESCO (Energy Service Company) and the company, they decided to stop all new projects in face of the current decline of oil price. The project which was proposed within PITAGORAS has to be therefore postponed for an extended period.

2. PITAGORAS DEMONSTRATION PLANT IN BRESCIA (ITALY)

2.1. INTRODUCTION

In the frame of the European funded PITAGORAS project (FP7, Smart Cities Programme) a real scale pilot plant for waste heat recovery from fumes of an Electric Arc Furnace (EAF) in a steel mill has been designed and planned. Waste heat is used to produce steam in a Waste Heat Recovery Unit (WHRU), which is then used for two different purposes: the steam goes through heat exchangers to deliver heat to the district heating network (winter time) or feeds the ORC unit to produce electricity (summer time).

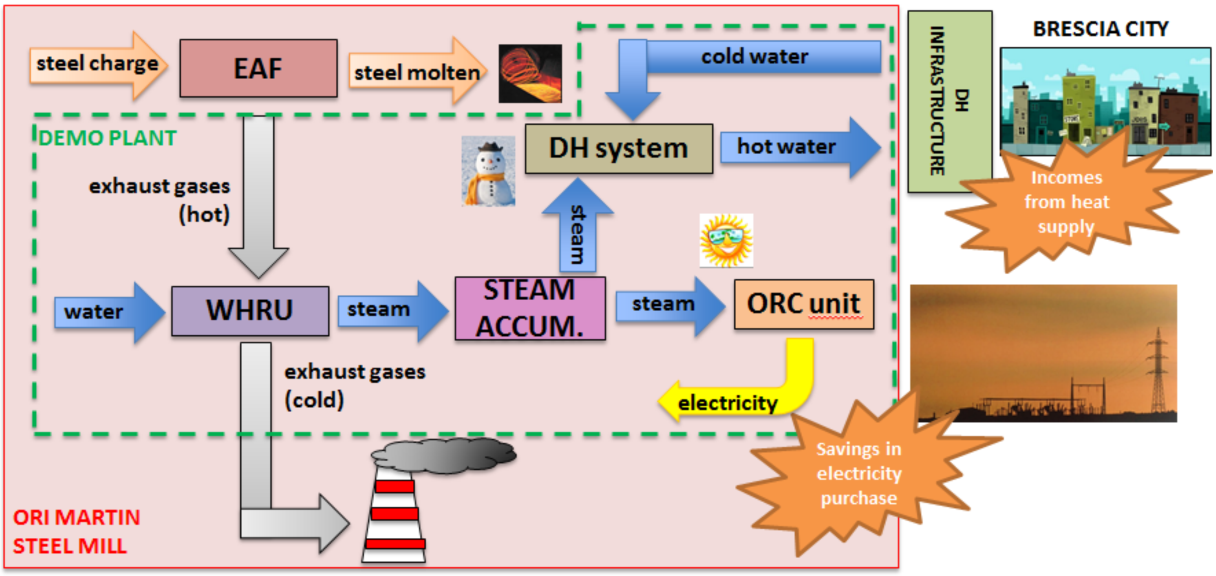

Figure 1. Conceptual scheme and battery limits of the PITAGORAS concept for waste heat recovery in a steel mill for electricity and district heat generation. Source: Tecnalia

The exhaust gases to be energetically valorized come from an EAF installed in the steel mill from ORI MARTIN located in Brescia (Italy). The flow rate for this flue gases (dry) measured by a venturi is approximately 100.000 Nm3/h, the average operating temperature of the flue gases at the inlet of the WHRU is about 500ºC and the average outlet temperature about 200ºC. After leaving the WHRU, flue gas flow goes to the quench tower and chimney through a buster, to ensure the correct draft.

It must be highlighted that the whole flue gases from the EAF are not directed to the WHRU: a part from them are conducted to the quenching tower directly.

Figure 2. EAF (left) and outlet duct from WHRU to Quenching Tower (right). Source: Tecnalia.

Flue gas particle concentration is charasteristically high at about 25 to 28 g/Nm^3, but also relatively large with about 0.3-1mm particle size. This means that caking of the WHRU pipes is probable; a cleaning system (mechanical or pneumatical) is therefore considered during the design phase of the system. The heat recovery potential is estimated in 9,1 MW$_{th}$, which generates a heat recovery capacity (steam) of about 52.000 MWh/year.

As it will be explained in points 2.2.1 and 2.2.2, the steam produced as a result of the flue gas heat exchange shall be used for electricity generation in an ORC cycle in summer (from May to September) and to produce hot water to be fed into A2A utility district heating (DH) network in winter (from October to April). This operation mode has been established as the most appropriate one for this specific site considering the boundary conditions of the system and the heat delivery contract with the DH utility. Produced electricity will be used for self-consumption of the steel mill.

It shall be also highlighted that the EAF operation is discontinuous, which means that the furnace stops every 50 minutes for the tapping phase. This is an important issue to be considered when designing the WHR system as these discontinuities must not reach the steam consumption points (ORC and heat delivery units)..

Tabla 1. Waste heat flow characteristics. Source: Deliverable D2.1. of PITAGORAS project

Waste Heat flow origin	EAF from steel mill owned by ORI MARTIN (Brescia)
Exhaust gas flow into WHRU (average)	100.000 Nm^3/h
Exhaust gas composition (average, % weight)	
CO2	3
O2	19
N2	77
H2O	1
Particle concentration	20-30 g/Nm^3
Inlet temperature (average)	500 ºC

Outlet temperature (average)	210ºC
Minimum outlet temperature	180 ºC
Heat recovery potential (design)	9,1 MWt
Expected waste heat production (steam)	52.000 MWh/year

2.1.1. Waste heat technology applied in PITAGORAS demonstration plant in Brescia

The general idea developed in this WHR system consists on recovering the heat potential from the exhaust flue gases coming from the EAF. This flue gas flow passes throw the WHRU, where flue gases circulate along the shell side exchanging its heat with water. This equipment is composed by one **Economizer** and four **Evaporators**, formed as well by different vertical tubes, where water circulates through. Water flow is fed from the water to the Economizer, where water flow is preheated before entering in the Steam Drum, which is a reservoir of water/steam at the top end of the water tubes.The four Evaporators are the main responsibles for the saturated steam generation.

Figure 3. Flue gas duct inlet to WHRU from EAF. Source: Tecnalia

Figure 4. ***Waste Heat Recovery Unit, formed by one Economizer (right side), four Evaporators (left side) and one Steam Drum at the top. Source: Tecnalia***

Due to the dirtiness of flue gases, the WHRU incorporates a **pneumatic cleaning system** at its bottom side (see red square in *Figure 5* below), which aim is the removal of dust placed on water/steam vertical tubes. The dust is totally removed from the system through a screw conveyor.

Figure 5. Pneumatical WHRU cleaning system. Source: Tecnalia

In order to decouple the discontinuities of the steam production and its use, a **Steam Accumulator** is installed. The recovered thermal energy is stored in this component and released to the ORC unit (in summer) and to DH heat exchangers (in winter) when required and fulfilling the loads requirements regarding stability, pressure and temperature properties, etc. This Accumulator operates between 10 and 24 barg and 185 and 224 ºC and has a storage capacity of about 3 MWh_{th}. Depending on the steam demand downstream, the pressure and temperature are modulated accordingly. The use of the Steam Accumulator in the system allows meeting the following requirements:

- Accumulation of the recovered thermal energy and release to the ORC unit or DH heat exchangers in periods with no or insufficient energy from the WHRU. In this way it is possible to supply the ORC a heat power with relatively small variations.
- Ensuring a controlled reduction of the heat load transferred to the heat receivers in a phased manner in accordance with a predetermined safety operation strategy in case of a sudden stop or failure of the WHRU or the EAF.
- Keeping the steam pressure in the Steam Drum as stable as possible, eventhough the temperature or flow of the exhaust gases are highly fluctuating.

There are two operating modes:

Charging phase:

Until the steam demand is less than the steam supply, the pressure and temperature inside the Accumulator increases. The vessel is loaded until the entire system reaches the set target value below the maximum pressure and temperature design values, i.e., until the Accumulator will be fully charged.

Discharging phase:

If the steam receiving is greater than its delivery from the boiler, the internal pressure of the accumulator drops. This results in a flash evaporation of the liquid, which results in steam available for the users.

The next important element after the Steam Accumulator is the **main distributor**, which takes the steam from the Accumulator and distributes to the loads: ORC unit in summer and DH heat exchangers in winter.

Figure 6. Steam Accumulator (left) and steam distributor (right). Source: Tecnalia

There is also an **emergency condenser** located in order to compensate the steam overload, where the steam condenses and is returned to the feed water tank as water. This condenser is actually working continuously.

The **feed water tank** stores the condensate water coming from the whole installation in order to feed the WHRU through a pump. In the top part from the tank, there is a deaerator, which aim is the removal of oxygen and other dissolved gases from the feedwater. Not only regarding purges from water tank, but also from Steam Accumulator and Steam Drum, a blowdown tank is installed in order avoid the concentration of impurities in the storage tanks.

Figure 7. Feed water tank and demister in the top part (left) and one of the boiler feed water pumps (right). Source: Tecnalia

The *Figure 8* below shows the process flow diagram (PFD) of the part of the system from the steam generation until the main distributor.

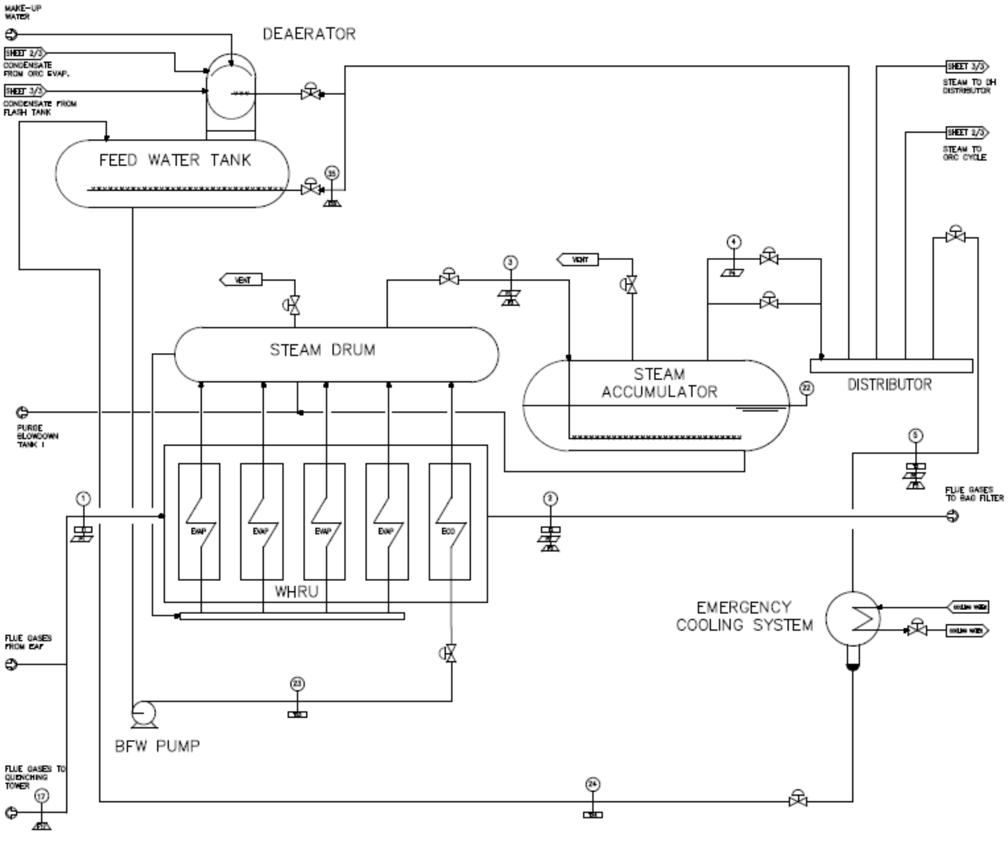

Figure 8. PFD from the WHRU and main equipment. Source: Tecnalia.

2.1.2. ORC system technical description

During summer time the pilot plant does not produce district heat. The waste heat in this period, from May to September, is used to feed the ORC unit and produce electricity which will be used for self-consumption. The whole ORC unit has been supplied by TURBODEN[1].

Technical average data are shown below:

Tabla 2. ***ORC system average production data. Source: Deliverable 2.3. PITAGORAS project.***

Working fluid	Silicone oil
Average incoming thermal power into ORC Evaporator	10,4 MWt
Input operating pressure /temperature	16 barg / 204ºC
Output operating pressure /temperature	15,8 barg / 107ºC
ORC system average net efficiency	17,5%
Average net Electric power output	1828 kW_e
Average thermal power to be dissipated in ORC Condenser	8460 kW_{th}
ORC average availability (during 5 months)	96%
Expected annual electricity generation	4200 MWh/year

The saturated steam from the main distributor is directed to the ORC Evaporator, where it exchanges its heat with the silicone oil (Hexamethyldisiloxane, $C_6H_{18}OSi_2$), which circulates through the internal circuit of the system. At ORC Evaporator inlet, this saturated steam is slightly pressurized by a control valve. At ORC Evaporator outlet, the condesate is also directed to the Postcooler in order to verify that the whole steam has converted to liquid. Then, liquid flows to the Deaerator and Feed Water Tank.

Regarding silicone oil internal circuit, it operates in the following way:

- At ORC Evaporator outlet, silicone oil is vaporized in order to enter to the Turbogenerator, where it is expanded to generate electricity. Pressure and temperature inlet level are 3 barg and 145ºC approximately.
- At Turbine's outlet, silicone oil has been expanded (lower pressure) but it still has high temperature (near 113ºC), which is taken in advantage in the Regenerator to increase considerably ORC cycle efficiency. Pressure level at Turbogenerator's outlet is 0,12 bar.
- In the Regenerator, the silicone oil exchanges heat with itself (hot side). At Regenerator's outlet (near 45ºC), the silicone oil decreases its temperature approximately 8 ºC in the ORC condenser (with the entrance of cooling water) and then, in order to be preheated before entering again in the ORC Evaporator (at about 92ºC), it is pumped to the Regenerator (cold side) as it is shown in Figure 9.

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[1] http://www.turboden.eu/en/home/index.php

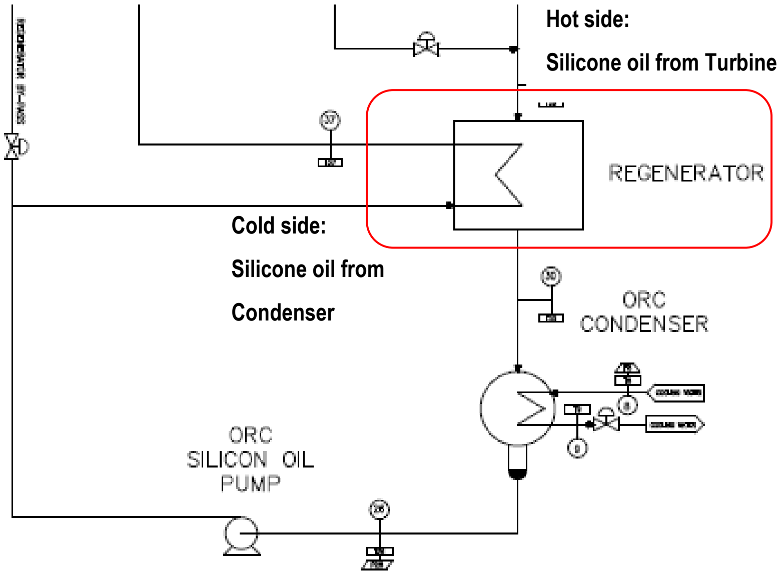

Figure 9. Detail of the ORC Regenerator scheme. Source: Tecnalia.

- As it has been estated before, after the ORC Condenser, silicone oil flow can flow towards different equipments:
    - The nominal operation mode is that the whole silicone oil flow directs to Regentaror. If this occurs, the silicone oil preheated in the Regenerator enters directly in the second preheater called High Temperature (HT) Preheater (LT is fully by-passed).
    - On the other hand, a small part of the flow can be directed to a first preheater called Low Temperature (LT) Split Preheater, where the silicone oil average ΔT is 70ºC aproximatelly (by the control valve located in the circuit). Then, it passes to the HT Preheater. In any way, the most part of the flow is directed to the Regenerator.
    - The last step is being evaporated in the ORC Evaporator, having an outlet temperature of about 145ºC.

Along the silicone oil circuit, a Turbine bypass has been expected in case silicone oil conditions are not the optimum at Turbine’s inlet.

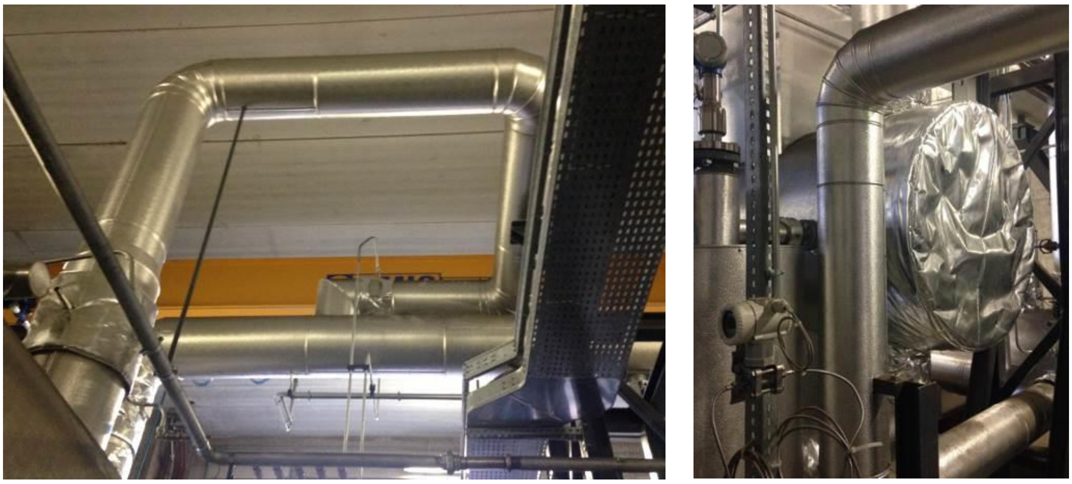

Figure 10. ***Steam inlet duct to ORC Evaporator (left) and ORC Evaporator (right). Source: Tecnalia.***

Figure 11. ***ORC Turbine and Generator (left) and ORC Evaporator shell and Condenser. Source: Tecnalia***

The electrical generator transforms the mechanical energy into electrical energy with high efficiency. It is directly connected to the Turbine with a flexible coupling in order to allow proper operation even in presence of any small misalignment with respect to the turbine shaft. Since the electrical generator is asynchronous, it is suitable to operate only in parallel with the electric grid, without possibility of island operation, and requires the absorption of reactive power from the grid.

A MV/MV Transformer Station, oil immersed with natural air cooling and suitable for outdoor installation is installed. Transformer Station follows IEC 60076-1 and CEI 14-4 norms.

All the pipes and equipments implemented in the ORC unit are insulated with insulating material lined with a metal sheet, in order to avoid thermal losses during heat exchange and hot fluid transport.

The sound pressure level of the ORC system in operation is lower or equal to 90±2 dBA, measured in an open field at a distance of one meter (1 m) from the turbogenerator boundary.

As a general idea of the ORC installed system, which includes the electricity generation during summer time, a general PFD has been developed, which includes the main equipment and auxiliary services (Figure 12). Moreover, Figure 13 shows a 3D scheme of ORC unit.

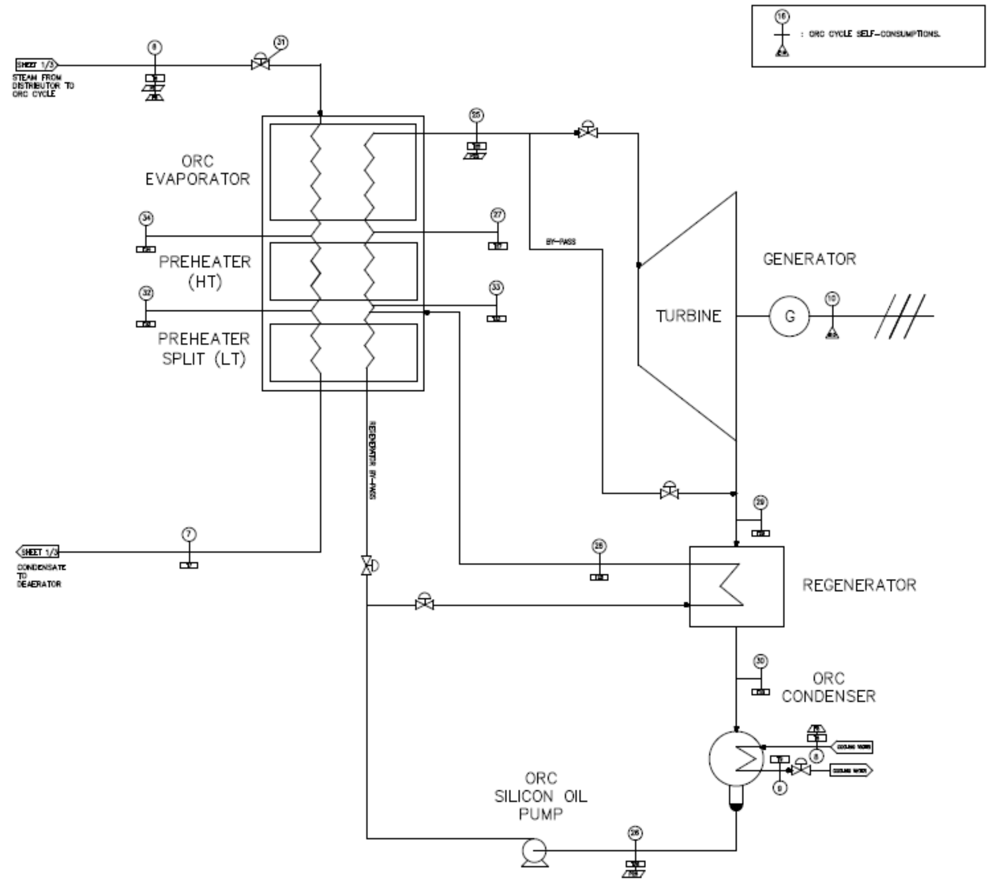

Figure 12. PFD from the ORC system implemented in the Brescia pilot plant. Source: Tecnalia

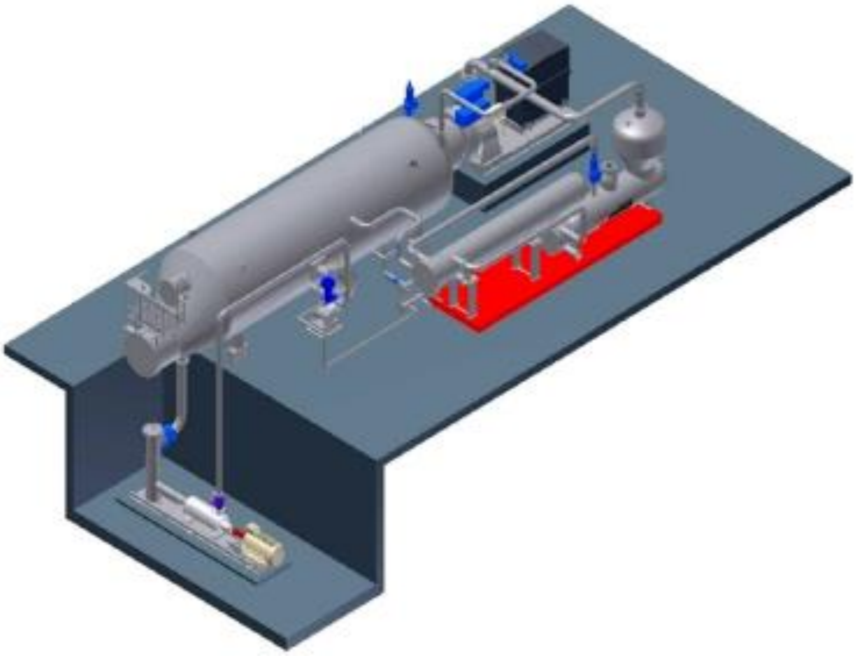

Figure 13. 3-D CAD plot of the ORC system. Source: Deliverable 2.10. PITAGORAS project.

2.1.3. District heat production and heat delivery to DH network

During winter time, from October to April, the ORC is not working and the steam is used for district heat production. According to first estimations, heat supplied by this pilot plant is expected to represent around 3% of the total heat consumed within the DH network. Technical average data are show below:

Tabla 3. ***DH system average production data. Source: Deliverable 2.3. PITAGORAS project.***

Thermal power heat exchangers (HX nº1 & HX nº2)	10 MW_{th}
Input operating pressure / temperature to HX nº 1 & HX nº 2	10barg / 185ºC
Average flow rate to DH network	140 m^3/h
Hot water average supply temperature to DH network	95ºC/120ºC
Hot water average return temperature from DH network	60ºC/ 85ºC
DH system average availability (during 6 months)	95%
Expected annual thermal energy generation	26.500 MWh_{th}/year

Tabla 3 shows the operating principle and main equipments of this part of the system related with district heat production. The saturated steam from the main distributor is directed to the DH system distributor, where the steam is divided into two flows and directed to the DH heat exchangers (HX nº1 and HX nº 2). Both units are equal and the design thermal capacity is 5 MW_{th} each approximately. At these condensing heat exchangers, the steam exchanges its latent heat with the water flow circulating within the DH network. The outlet condensate from both heat exchangers is stored in a Flash tank. In the upper side of the Flash tank, there is a Condenser, where the condensate exchanged its remaining heat with the return cold water from the DH network, in order to be preheated before entering HX nº 1 and HX nº 2. Flash Tank outlet condensate is returned to the Deaerator, in order to reject possible dissolved gases, before entering in the BFW tank.

Supply and return flow temperatures of the DH network vary during the year. The average supply/return temperatures are around 95ºC-120ºC/60ºC-85ºC, depending on the month of the year. The return flow enters first the Condenser and the two heat exchangers afterwards.

Figure 14. Steam pipes to DH system (left) and DH system equipment cabinet (right). Source: Tecnalia

Figure 15. Steam-water heat exchangers (HX nº 1, left and HX nº 2, right). Source: Tecnalia

Figure 16. Flash Tank and Condenser in the upper side (left); water circulating pumps to Condenser (right). Source: Tecnalia

The following *Figure 17* shows the PFD of this part of the system regarding the district heat production.

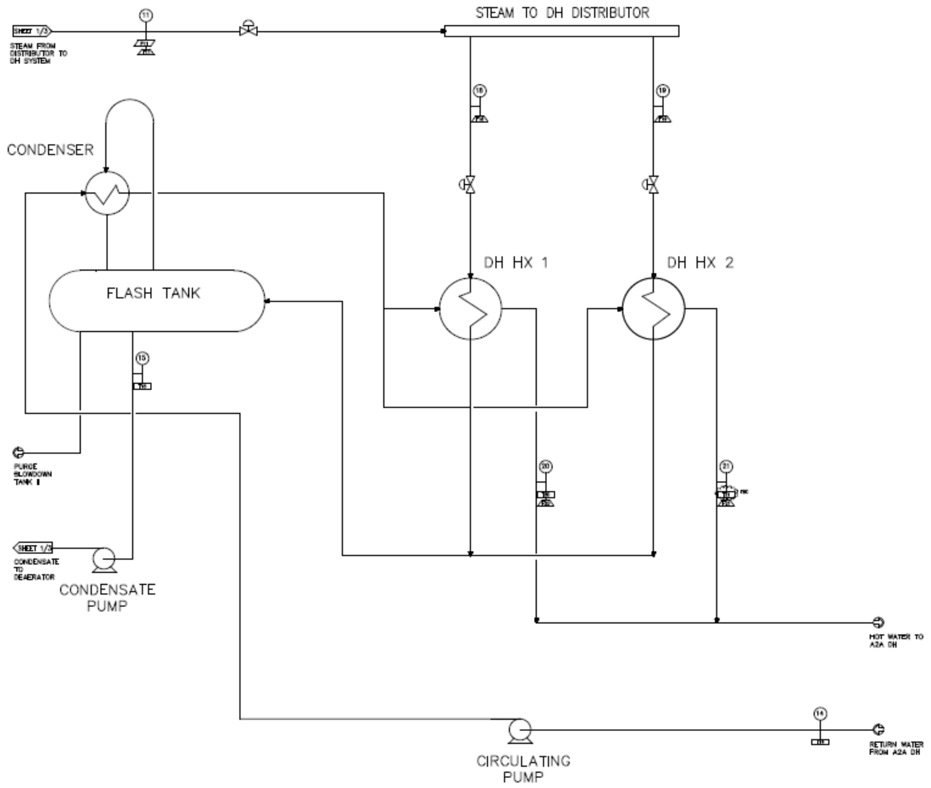

Figure 17. ***PFD from the DH system implemented in PITAGORAS project. Source: Tecnalia.***

2.2. OPTIMIZATION OF THE WASTE HEAT RECOVERY SYSTEM: ENERGY MANAGEMENT SYSTEM

2.2.1. Introduction

Optimization possibilities of the overall system have been analyzed. An Energy Management System (EMS) for the Brescia pilot plant has been developed based on Artificial Intelligence algorithms as a decision support tool providing the plant operator with necessary data for scheduling the plant optimal operational strategy. The main objective of the EMS is to maximize the incomes to the plant operator in order to minimize the payback through the most efficient exploitation of all the energy flows transferred in/out of the plant.

Efficient energy management is a complex task consisting of energy coupling (heat and electricity), multiple operational objectives (running costs, working efficiency, emissions) and multiple time scales (short term, mid- and long term). The more reliable forecasts of the load demand and energy prices as well as plant capacities are available, the better decisions can be made to schedule the power dispatch.

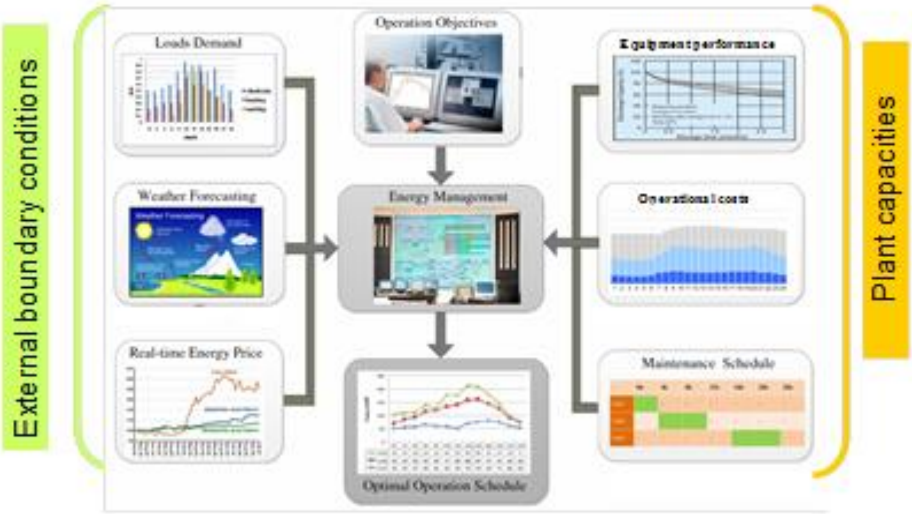

Figure 18. ***Concept of Energy Management System development. Source: CIM-MES.***

The general concept of EMS is illustrated in *Figure 18* which shows the information sources taken into account in the energy management system architecture.They include load demand, weather forecasts, real-time energy prices, actual operating conditions and maintenance schedule of the plant capacities and based on these data, EMS generates optimal operation schedule for the selected operation objectives.

This EMS supportive tool is composed of three main modules:

- modules for estimation of future load demand (heat & power) and for prediction of heat, electricity and fuel prices in energy market; simulation module for prediction of system performance and estimation of the available amount of heat and electricity production depending on the plant capacities, which allows simultaneously to estimate the operating costs, emissions etc.
- optimization module for optimal allocation of the load between individual production units and for computation of optimal production schedules. The module solves the CHP (Combined Heat and Power) dispatch problem without restrictions on the shape of cost functions and constraints as a general optimization problem with nonlinear cost function and nonlinear constrains.

The EMS developed within the project is assumed to focus on short-term (24 hours – 1 week) and mid-term (1 week up to 12 months) planning and the plant capacities as well load and energy price forecasting period is considered accordingly. Additionally, the system allows predicting the short-term behaviours of the input parameters of the control system as well as demand required by the other customers. The proposed solution is scalable and portable. It has been tested on the lab scale (simulation environment) and will be demonstrated for the demo plant with real data from monitoring system (on-going activity within the project, to be disseminated in a later stage of the project).

To predict the plant equipment performances EMS implements simulation models based on artificial neural networks (ANN). Artificial neural-network models may be used as alternative methods in engineering analyses and predictions and they operate like a “Black Box" model (*Figure 19*), where no particular knowledge on the physical properties of the system itself is required.

Figure 19. ***ANN as Black-Box model***

They learn the relationship between the input parameters and the controlled and uncontrolled variables by studying previously recorded data, in a way similar to how the learning process of a human brain is performed. Within the project, a two-stage approach was applied to learn the ANN models for Energy Management System development:

- Learning of ANN on the base of simulation results from TRNSYSTM / HYSYSTM simulation systems
- Re-learning ANN with the use of real data from monitoring system of the plant. See *Figure 20*.

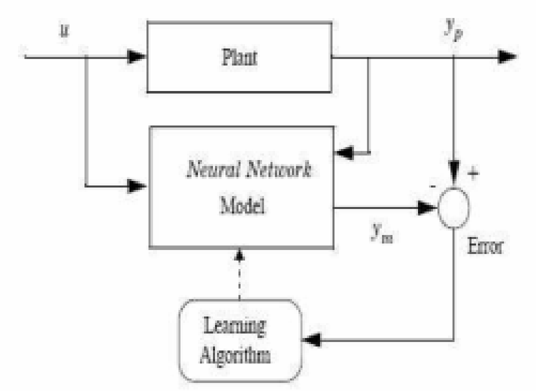

Figure 20. Scheme of re-learning ANN models based on real plant data.

2.2.2. EMS for Brescia demonstration site

Energy Management System for Brescia plant has been developed for the installation, whose schematic drawing is given in *Figure 21*. The scheme illustrates energy flows between the main WHRU components and the plant environment. The components considered in EMS optimization procedure are inside the area enclosed by red dotted line.

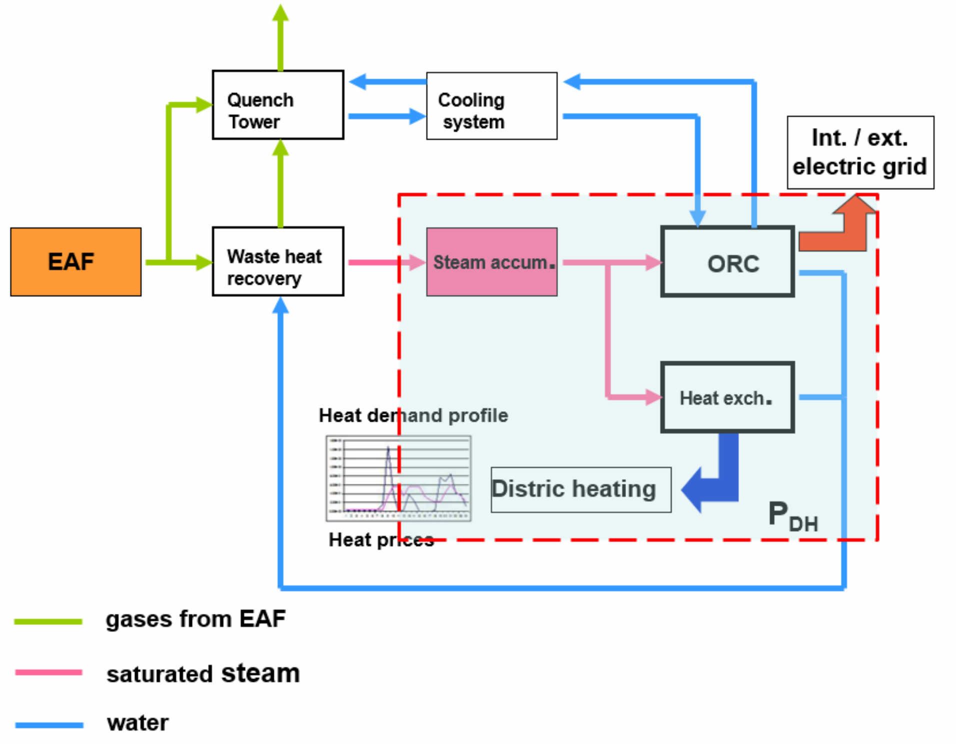

Figure 21. Waste heat recovery system in ORI Martin steel mill in Brescia - scheme of the main energy flows. Source: CIM-MES

The operation strategy of the plant with power-only production in summer and heat-only production in winter has been concluded as being the economically most sensible system for Brescia plant. Additionally, however, the potential of a more flexible operation strategy has been evaluated. In contrast to the initially defined strict seasonal operation mode (winter-heat production, summer-electricity production), the alternative of producing both district heat and electricity in winter time has been considered (and implemented into the EMS), which can bring the additional operating profit thanks to the power production by ORC when power is still available after fulfilling the heat supply requirements.

The system works based on the following input data, which determine external conditions for WHRU and ORC unit operation:

- Weather forecasts which define DH heat demand,
- Current and forecasted energy prices,
- Labor and maintenance costs of ORC unit,
- WHRU monitoring system data and historical data.

Based on the input data the EMS application performs checks in a prescribed time horizon of the thermal power input to the system and demand of the heat loads (mainly DH grid). If the input power is higher than the required output power, the EMS advices start-up of the ORC unit and computes its optimal load alongside with the forecasted economic profit. On the other hand, if the heat power input varies and may be too low for successful operation of the installation for both DH and ORC unit needs, the EMS performs additional checks for the steam accumulator performance and operation. Small deficiencies in input thermal power may be covered by the heat accumulator and EMS attempts to foresee optimal operation scenario for such a case. Eventually, it delivers to the operator information on the optimal system operation which encounters all WHRU components.

The output of the EMS is optimal operation strategy which maximizes economic profit through the optimal split of heat flow from steam accumulator into two flows:

- P_{ORC}: heat energy supply ORC unit for power production.

- **P_{DH}**: heat energy transferred to District Heating.

This strategy is delivered to the operator, who is in charge of making ultimate decisions on the installation operation. The characteristic of optimum values of "**P_{ORC}**" and "**P_{DH}**" over the considered operating period ***T*** allow him to select new set-points of control valves. The optimization result will be the vector *u(t)*, which defines the operation schedule of ORC and points out when the ORC should be turn on / turn off over the period *T*.

The scheme of energy flows is shown in *Figure 22:*

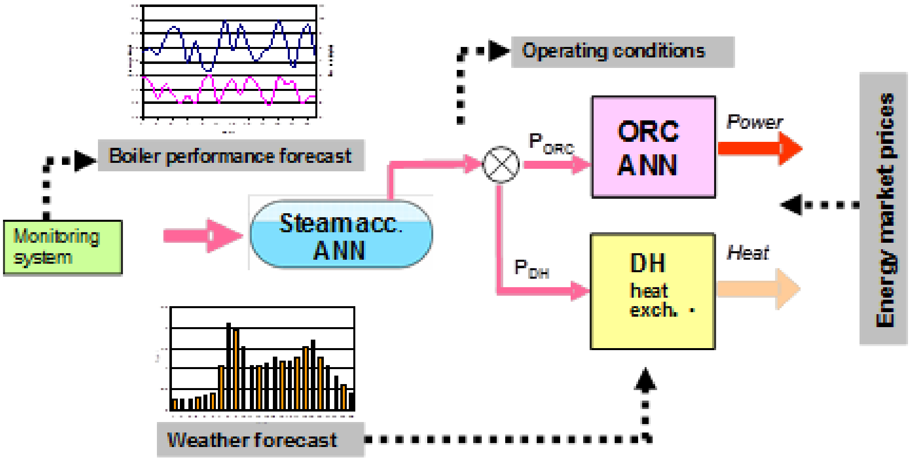

Figure 22. ***Scheme of energy flows in Brescia plant (computation model for EMS). Source: CIM-MES***

The external conditions that strongly influence the EMS results are heat and electricity prices. These two factors allow determining how profitable it is to produce electricity for internal demands (high electricity prices on the external market mean bigger savings in case of internal production) and state, how profitable it is to produce heat for district heating grid.

The most important conclusions referring to Italy market are:

- Average electricity prices in Italy are high and a value of 180€/MWh is representative, which includes all taxes and levies.
- Prices fluctuate strongly between both months and hours of a day.

For the EMS simulation purposes, the heating season 16.10.2014 – 15.04.2015 has been selected.

The average daily heat demand versus the average daily temperature was determined, which is shown in *Figure 23*. The EMS optimization was performed for mid-term operating scenario plant operation, and the first 39 days of selected period have been investigated.

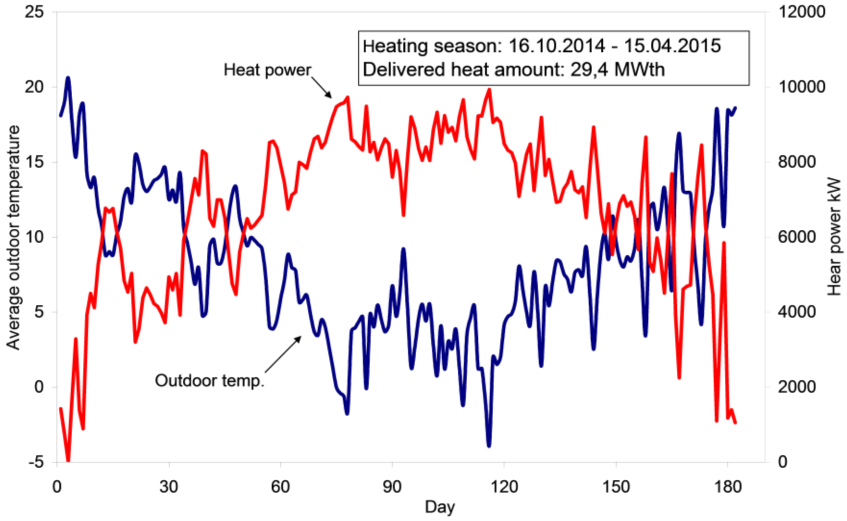

Figure 23. Average daily outdoor temperatures and heat demand in Brescia DH during heating season 16.10.2014-15.04.2015.Source: CIM-MES.

Based on data from the monitoring system, which include 10-minutes information on available heat amount to be recovered in WHRU and using the heat demand profile, EMS delivers information available waste excess heat to be used by ORC (see *Figure 24*). It can be noted that the majority of time thermal power input outweighs DH demand. In a lot of periods, the difference is significant and sufficient to allow ORC running.

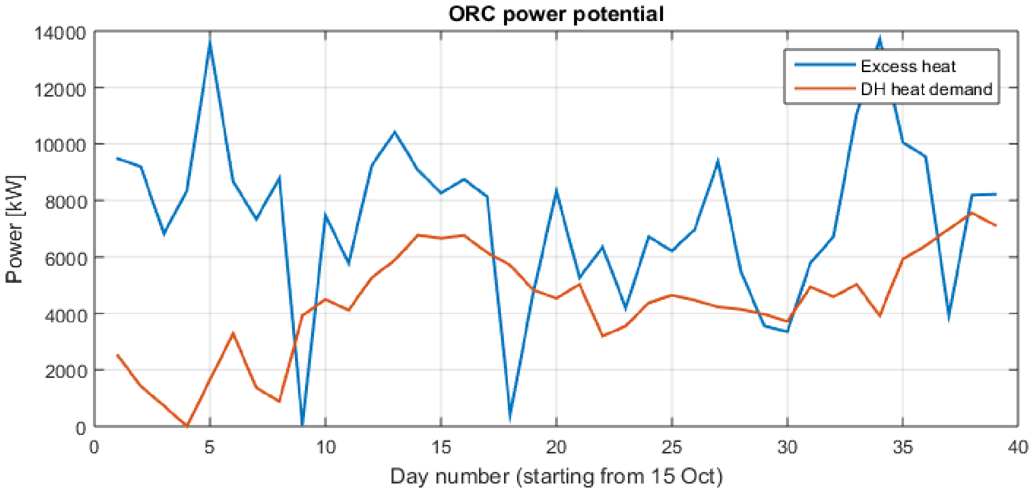

Figure 24. Comparison of heat power demand in DH grid and available thermal power from WHRU. Source: CIM-MES

These results imply that for average net electricity prices in Italy (for second half of 2014) of 173,5 Euro/MWh and minimum heat power input of 3.144 kW to ORC (LC1 load case), we can estimate the additional profit from the ORC unit operation as 46.45 €/h.

To calculate the economic profit in more detail, apart from the heat and power prices, the operational and maintenance costs were taken into in analysis, including the ORC starts-up and shuts-down costs. Based on these input data, EMS calculates the minimum ORC operation time, when the profits form ORC running outweigh the regular maintenance and additional start-up / shut-down costs. The time intervals, when the ORC can successfully run over the analysed period are pointed in *Figure 25.*

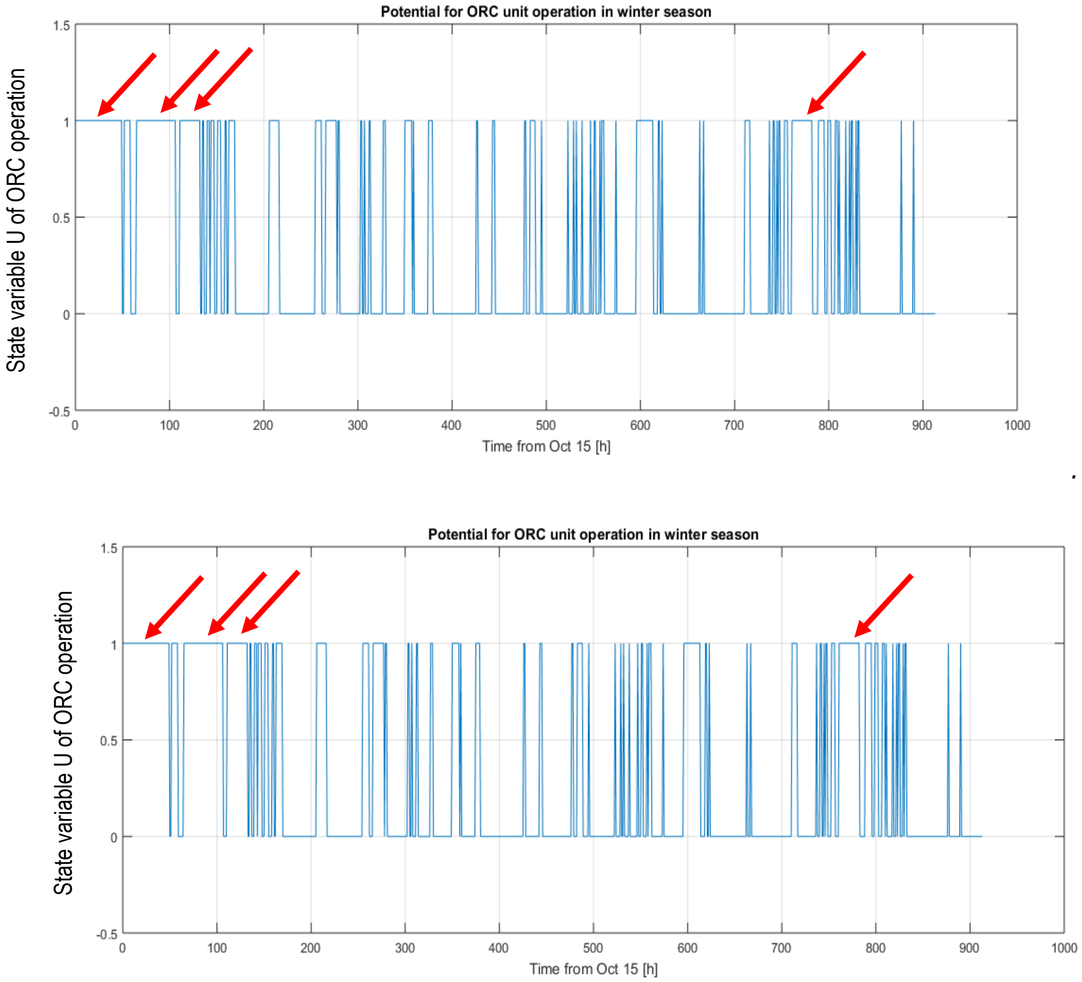

Figure 25. ***Possible ORC operating schedule in the heating season; 1 – ORC "ON", 0 – ORC"OFF". Source: CIM-MES***

The total net savings (economic profits minus maintenance costs) due to additional electricity production during heating season, has been estimated at the level of 35.000 € for the analysed period Oct 15th – Nov 24th 2014.

2.2.3. Conclusions

The developed EMS has high potential for the optimization of similar plants but it should be taken into account that the electricity price versus the operational costs, is a key variable behind the obtained results and therefore the estimated benefits are strongly related to the conditions and market surrounding of a given facility. Real electricity prices for industries may strongly vary from one site to another and these factors must be accounted for.

Brescia case is characterized by having two very strict and separate operation modes – one strategy for winter season and one for summer period, which strongly restricts optimisation potential. Other similar plants with more flexible operation modes would enable the EMS to achieve greater economic savings and would reveal greater potential for energy management and optimisation tools.

2.3. ASSESSMENT OF POTENTIAL SITUATIONS FOR THE APPLICABILITY OF THE DEVELOPED PITAGORAS CONCEPT

2.3.1. Introduction

This chapter is a synthesis of the findings done within the task 2.6 of the PITAGORAS project (Deliverable D2.13. of the PITAGORAS project). The approach for this task was to optimize the integration of the PITAGORAS concepts within DH networks by means of simulation in order to spot the best potential situations for the applicability (and hopefully, replicability) of the developed concept.

This is a very complex problem, since boundary conditions (energy prices, meteorological conditions, urban plot…), as well as sizing criteria of the different components of the system interact between them and evolve with time. The methodology followed is inspired by the recent debates in the simulation community around the topic of what conclusions can justifiably be derived from a mathematical model (A.Saltelli, 2000). A statistical approach has been therefore followed with the models developed for which thousands of simulations with varying input parameters have been launched and assume that the properties of the resulting results distribution are those of the concept simulated.

2.3.2. General approach and assumptions

The main objective of the performed simulations is to conclude general behaviours and tendencies for the PITAGORAS concept developed for the Brescia pilot plant ("medium temperature waste heat recovery with ORC"), based on the results obtained from the many different situations considered. 15 European cities have been considered in the study and a sensitibity analysis of the main variables of the system (such as electricity and gas prices, system size, running hours, type of industry, etc) has been carried out. In Annex I the energy prices and CO2 emission factors assumed in the study are shown.

Three different operation strategies have been modelled, representing three different approaches for exploiting the available waste heat:

- Full electric system: all the waste heat is used to operate the ORC for strictly electricity generation
- CHP mode: the turbine rejects heat at a higher temperature (90ºC), which is in time recovered and injected in the district heating network. Hence, the system is generating both electricity and heat during the whole year
- Seasonal mode: this is the operation strategy of the demonstration plant in Brescia. During winter period, the waste heat is used to feed the district heating network, and in summer, the waste heat is used for generating solely electricity through the ORC unit.

The following points should be pointed out in order to appropriately understand the results reported in section 2.4.3.

- Electricity prices provided by Eurostat have been used for the analysis. It is worth to be noted that they seem quite high for the real world values that one can encounter on industrial facilities, especially for big consumers. This means that the obtained results should be interpreted with care. It should be mentioned for example the location factor: basically what is behind that label is an electricity price, a gas price and a specific demand. While the demand is representative of the local climatic conditions, the electricity and gas price for a given user in that location will be probably different from the values considered here; it should be therefore interpreted with care.

- It is assumed that all the electricity produced yields an economic revenue at the same price as the electricity costs. In the real world this would depend on the national legal framework, exploitation model and if the electricity is self-consumed within the generator facilities (assuming he is also the system owner) or exported to be consumed by thirds via electric grid.
- In order to quantify the emissions avoided by the solution under study it is necessary to compute the emissions associated with a reference system. A central natural gas fuelled boiler system and a conventional distribution DH network operating on an average temperature of 90ºC forward and 60ºC return has been considered as reference system

In order to assess the relative potential of the analysed system two main metrics have been selected to evaluate the economical and environmental potential:

- Levelized Cost of Energy [€/kWh]: this is the Net Present Value of the energy produced by the system over its lifetime, incorporating all the costs incurred within it's lifetime as well as all the energy produced, discounted with a given rate. Analitically, it is defined as:

$$LCOE = \frac{\sum_{i=1}^{n} \frac{(I_i + M_i + F_i)}{(1+d)^i}}{\sum_{i=1}^{n} \frac{E_i}{(1+d)^i}}$$

Where:

n = lifetime of the system.

I_i =Investment costs for the year i.

M_i =Operation, financial and maintenance expenses for the year i.

F_i =Fuel costs for the year i.

E =Energy produced for the year i.

d =discount rate.

The variable $LCOE/LCOE_{ref}$ has been used to plot the results (section 2.4.3.), which is the quotient of the LCOE for the simulated PITAGORAS system and the LCOE of the reference system.

- Cost of the CO_2 avoided [€/tonCO_2]: this is the overcost (if positive) per ton of CO_2 avoided. It is equivalent to the necessary cost of CO_2 emissions in the market to even the cost with the reference system:

$$CostCO_2 = \frac{(LCOE - LCOE^{ref}) \cdot Load}{CO_2^{emissions,ref} - CO_2^{emissions}}$$

Where:

$LCOE^{ref}$ = Levelized Cost of Energy for the reference system

$LCOE$= Levelized Cost of Energy for the system studied

$Load$ =Total anual load met by the system

$CO_2^{emissions,ref}$= Yearly CO_2 emissions by the reference system

$CO_2^{emissions}$= Yearly CO_2 emissions by the system studied

2.3.3. Potential situations for the applicability of the PITAGORAS concept

This chapter presents a summary of the main results that have been obtained from the comprehensive simulation work that has been performed.

In *Figure 26* the cost ratio distribution is represented to have a picture of how often profitable results are obtained. It is observed that there is a good probability that the PITAGORAS concept overcomes, from an economic point of view, the classical solution defined as reference system. All values with a cost ratio below 1 have better economic results than the reference, and they account for a 36% of the sample, quite good considering that the input cases are defined randomly.

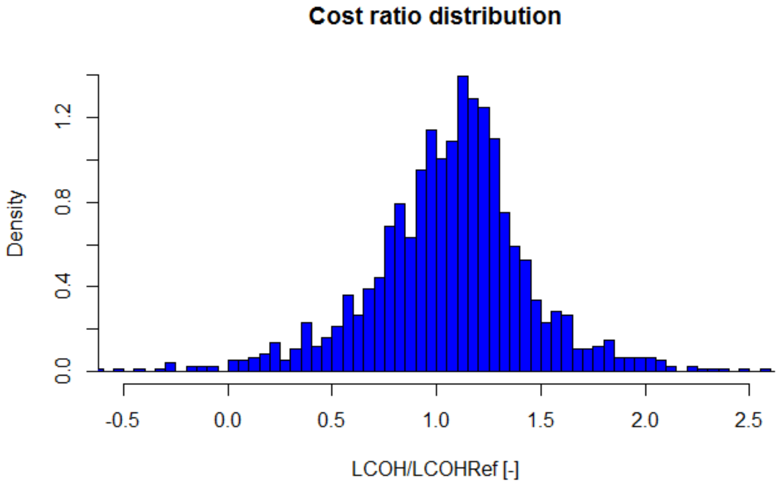

Figure 26. ***Cost ratio distribution. Source: Aiguasol.***

The following figure shows the same parameter (cost ratio) but split into different locations. A clear connection is not observed between this variable and the different locations. But an interesting conclusion could be got from the figure: in all simulated locations is possible to find application for this concept.

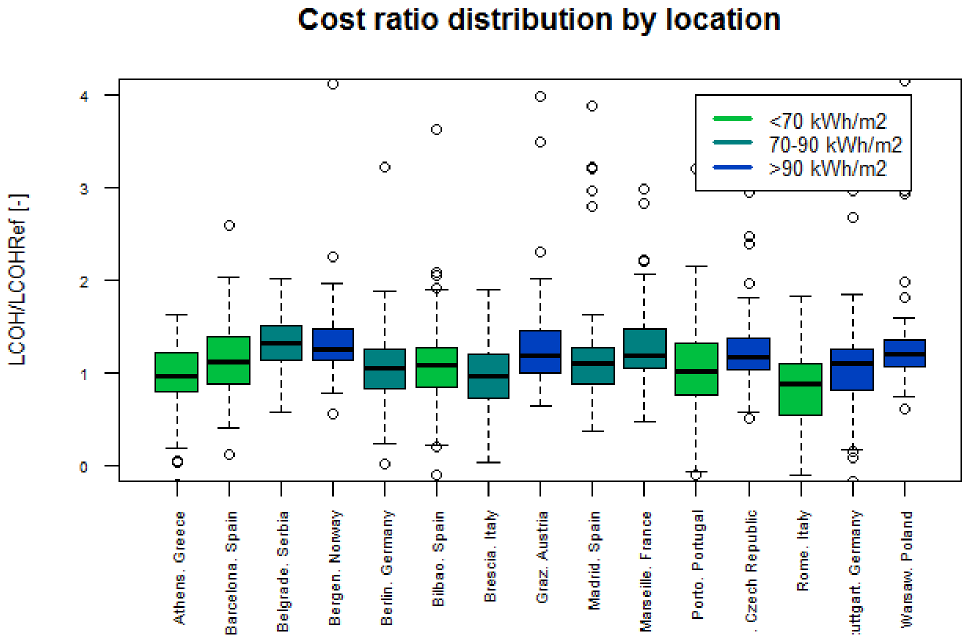

Figure 27. Cost ratio distribution by location. Source: Aiguasol.

On the other hand, the response of the system to the three different operation modes described above has been assessed. The results are shown in the figures below:

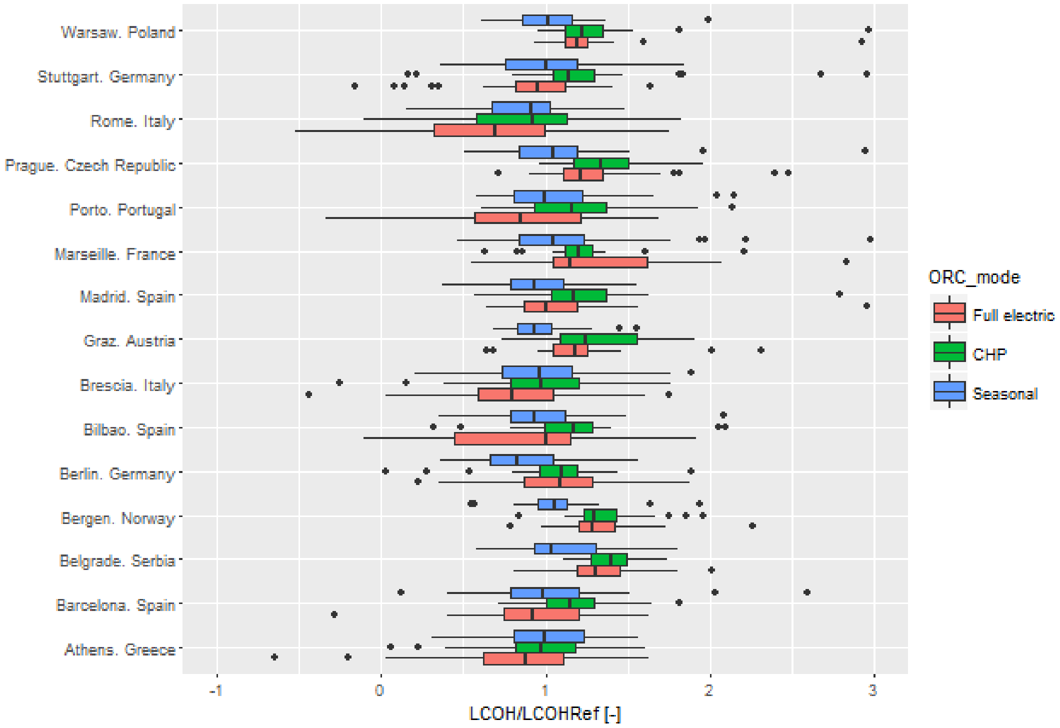

Figure 28. Cost ratio by location and operating strategy. Source: Aiguasol.

In *Figure 28* it can be seen that the most profitable situations appear systematically for full electric operation in warmer climates of high electricity price countries. For most locations, the CHP operation is (as a trend) the worst performing operational mode for the ORC, but in a few situations, it becomes competitive against a full electric operation. However, in these cases, the seasonal mode performance appears, a priori, more attractive. For colder climates with low electricity prices, this seasonal operation seems to be the best solution[2].

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[2] It is important to emphasize that electricity price used comes from Eurostat and seems quite high for the real world values that one can encounter on industrial facilities, especially for big consumers, so the location factor must be interpreted with care.

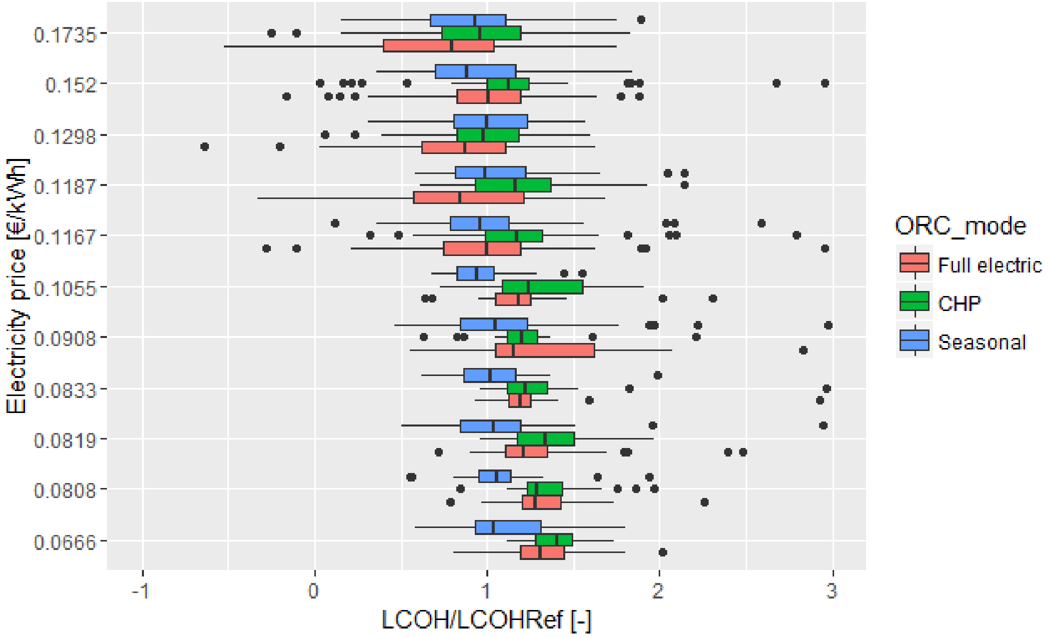

Figure 29. Cost ratio by electricity price and operating strategy. Source: Aiguasol.

In case the electricity price is represented in the vertical axis, as it is shown in *Figure 29* above, it seems that the seasonal operation is relatively less dependent on the cost difference, while the full electric operation is far more sensible. The CHP operation appears to be somewhere in between. Looks like under a difference of around 7 c€/kWh the seasonal mode surpasses the full electric, while over that, either a full electric or a seasonal might be the most appropriate.

Regarding environmental benefits, the following graph shows the distribution of the CO_2 emissions for both the simulated and the reference system. There is a noticeable number of situations where, as a whole, the system yields a negative CO_2 balance. This is because it has been assumed that all the electricity exported is reducing the emissions according to the national grid mix. It is believed that, given the proper conditions, it is possible to have a 0 carbon neighborhood, or even negative with this concept solution.

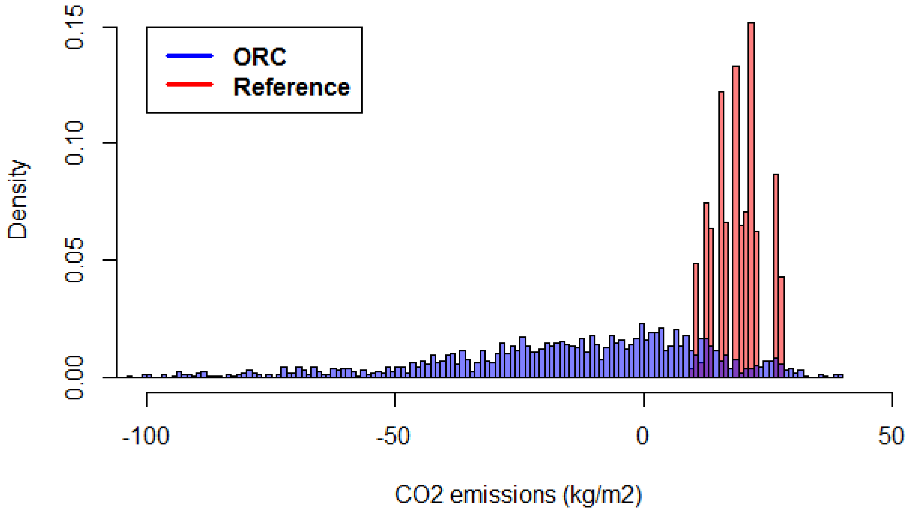

Figure 30. Specific district CO2 emissions. Source: Aiguasol.

The following figure shows the avoided CO_2 emissions as a function of the location:

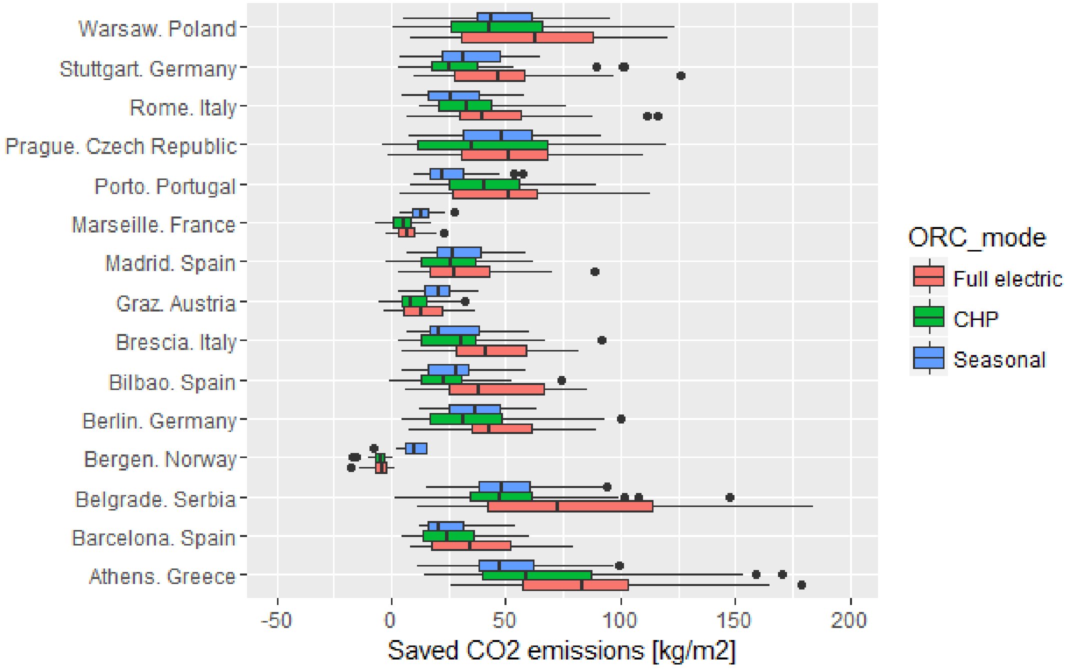

Figure 31. Avoided CO2 emissions as a function of the location. Source: Aiguasol.

The above figure clearly underlines how the response is dominated by the national electricity emission factors. Essentially, the higher the electricity factor the higher the emissions saving.

Under the considered assumptions, the obtained results reveal that the analyzed system may be a very interesting solution. Under many circumstances it can be economically feasible and highly contributing to reduce the equivalent CO_2 emissions. In all simulated locations it is possible to find application for this concept. The restriction comes from the availability of medium-high temperature waste heat, which will be in any case available at industrial sites, sometimes too far from cities and urban areas, which may limit the number of potential applications for this system.

The strong correlation of the system response with the electricity price needs to be specifically outlined. It should not be forgotten that the presented results are connected to the energy prices provided by Eurostat, which seems quite high for the real world values that one can encounter on industrial facilities, especially for big consumers.

The main outcomes are summarized in the following points:

- **Energy price** is by far the most important variable. The difference between electricity and gas price has been used within the study to analyze the influence of the energy price. As expected, the higher the difference the better the results of the ORC concept, but the tendency is not as dominating as it is found for other variables. The reason is that three different operation modes are considered, and when one of them performs worse, there is another one that improves.
- As expected depending on the energy price one **operation mode** or other fits better. The most profitable situations appear for full electric operation in warmer climates of high electricity price countries. For most locations, the CHP operation is the worst performing operating mode for the ORC. For colder climates with low electricity prices, this seasonal operation seems the best solution.

Other issues have been also estudied along this analysis, but with less influence as elecricty/gas prices and operation mode. The conclusions are the following:

- The results show that the best economic performances are associated with big turbine sizes, but this is not a necessary condition as good results for all the range of turbine sizes simulated have been found.
- The **availability** of the system becomes very relevant, since it is difficult to find profitable situations for less than 5000 h/year, but for full year operation (8017 h), the perspectives are very good: around 50% of the simulated cases become economically feasible.
- The **Balance of Plant** (BoP), which represents the investment costs of the system in relation to the turbine costs and is abstractly related to the properties of the waste heat source (temperature, corrosion, etc.), which represents different industrial applications. It has been observed that even for industrial applications with high value of BoP (i.e., cement plants), it is possible to encounter economic feasible situations for this kind of plants. Under the considered assumptions it can be concluded that these systems are not limited to certain applications.
- It has been shown that the heat demand has weak influence, but in general the pattern is that lower heat demands show better results. The reason is that for lower heat demands the electricity production (and consequently the incomes due to it) has a higher weight in the business model. This conclusion must be interpreted with care as it is directly linked to electricity and gas prices.

3. PITAGORAS SYSTEM CONCEPT DEVELOPED FOR KREMSMÜNSTER (AUSTRIA)

3.1. SITE DESCRIPTION

Kremsmünster is a town in the Austrian state of upper Austria with a population of 6.500 inhabitants approximately. Currently 65% of the thermal energy consumed in the city is covered by district heating (DH) (≈20 GWh/year). The main heat sources for the city district heating are the followings:

- CHP plant for electricity supply of an oil and gas company (RAG).
- Biomass heating plant.
- Waste heat from a glass manufacturer.

RAG is the Austrian oldest oil and gas company. Its core areas of business are oil and natural gas exploitation, production and storage. 5km to the south of Kremsmünster, RAG operates an oil and gas production facility for the processing of natural gas, which is indeed the site for the PITAGORAS pilot plant. The industry area of RAG in Kremsmünster, called KRIFT, is shown in *Figure 32*.

Figure 32: Overview of RAG premises including neighbourhood – site plan of KRIFT

To cover the electricity demand of their facilities, they operate a gas fired CHP plant with maximum power of 2.400kW$_e$ and 2.650 kW$_{th}$. The thermal output of the CHP plant (15 GWh/year) covers around 75% of the district heating supply of the city of Kremsmünster and it is as well partly used for self-consumption (oil production station and preheating of the oil storage tanks). There is as well a gas boiler for peak loads in winter time.

Within the PITAGORAS project a large scale solar plant was intended to be realized at the facilities of RAG, with the objective of enabling a reduction of fossil fuels and increasing the use of RES in the internal heat loads of the industry as well as in the city DH network supply.

The main loads for the PITAGORAS solar plant are the following:

Tabla 4. ***Main heat loads for the PITAGORAS solar thermal plant.***

Heat load	Energy demand *
Heat consumer 1	1.952 MWh/year
Heat consumer 2	6.098 MWh/year
Heat consumer 3 **	16.929 MWh/year

* Data from 2013
** Heat consumer 3 = District Heating network

The monthly data of the different loads are shown in the figure below:

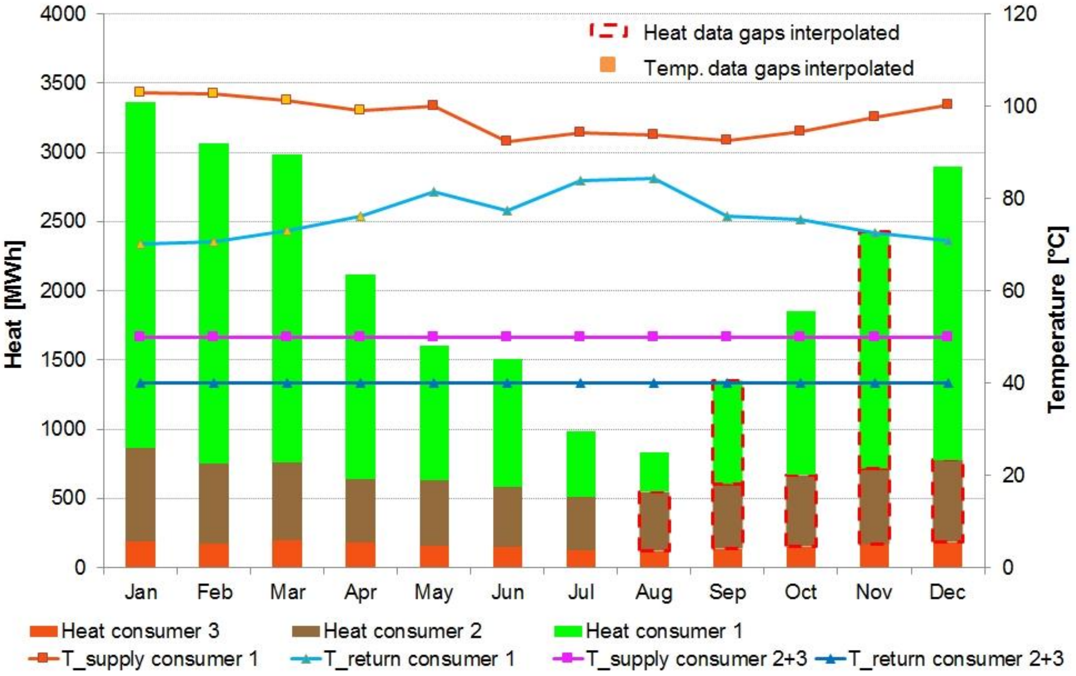

Figure 33: Load data of hte KRIFT plant in monthly sums, based on the operation data of 2013. Source: Solites.

It should be noted that this work aims at developing a solution that can be replicable for other Smart Cities. The heat delivery to the city DH network is therefore an objective that is intended to be fulfilled, although knowing that the high temperatures related to this heat load compared to the other loads that require lower temperatures have a negative impact on the solar system performance.

3.2. CONCEPT ASSESSMENT AND CONCEPTUAL DESIGN OF THE PLANT

3.2.1. Reference system: preliminary layout

The schematic of the system layout is shown in the following figure. The energy produced by solar thermal collectors is delivered via pipes to a solar heat exchanger by a variable mass flow pump. The heat transfer fluid in the primary loop is a mixture of water and glycol in order to protect the system from freezing. In the secondary loop on the right side of the solar heat exchanger pure water is used for the heat transfer. A variable mass flow pump runs the mass flow of the secondary loop in order to meet the temperature requirements of the heat load. The produced heat is stored in a buffer tank, which feeds the three loads (Tabla 4) according to the specific requirements in each case.

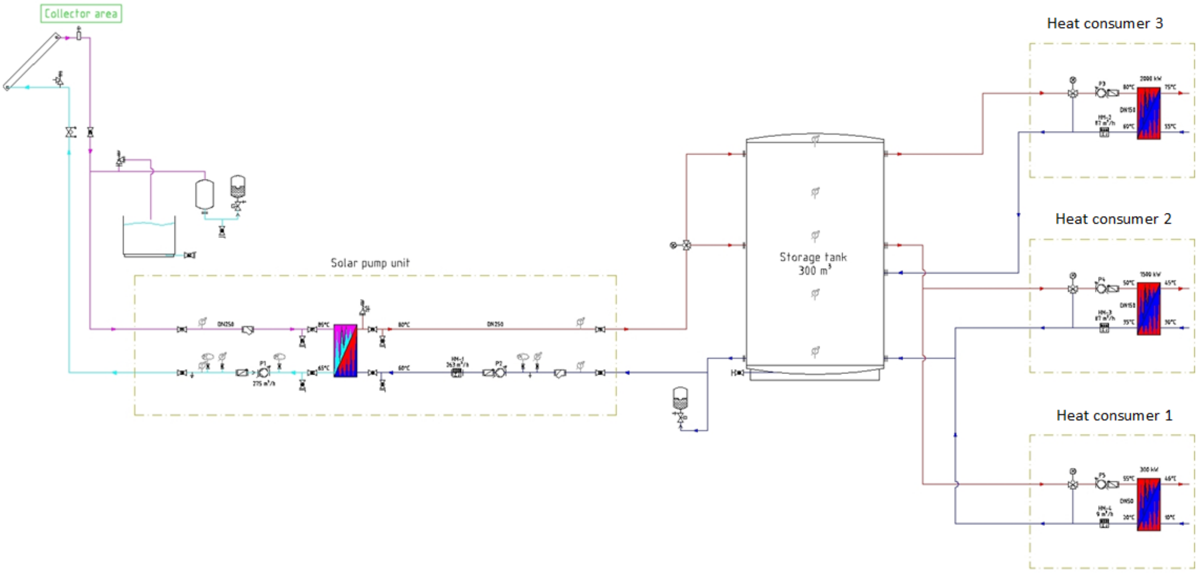

Figure 34: Hydraulic concept for the integration of the solar thermal plant in KRIFT. Source: Solid.

According to the initial calculations from SOLID a preliminary layout with a total aperture area of 9.377m^2 of solar collectors (10.000m^2 of gross area) and 300m^3 of buffer storage was defined. The solar collector field is ground-mounted. The collectors are facing south with a slope of 30°. *Figure 35* shows the expected energy flows for the preliminary system layout that were derived by system simulation with TRNSYS (Klein, 2010).

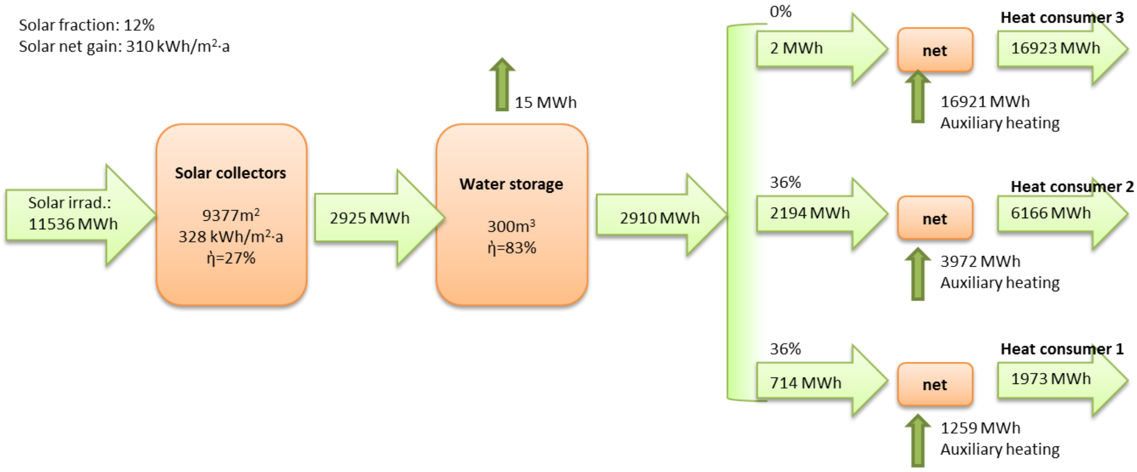

Figure 35: TRNSYS simulation results for the reference case visualized in form of an energy flow diagram. Datasource: Solites, Grafics: Tecnalia

The solar irradiation on the entire collector aperture area amounts to 11.536 MWh/year. The solar collectors with an aperture area of 9.377 m^2 can deliver 2.925 MWh to the buffer storage, which means a solar net gain of 310 kWh/m^2. The average collector field efficiency amounts to 27%. The water storage with a water volume of 300 m^3 is stored by 2.925 MWh/year of solar thermal energy. Due to heat losses, it can deliver 2.910 MWh/year, which is delivered in different fractions to the three possible heat sinks. The heat from the storage is delivered to the heat consumer 2 taking 2.194 MWh per year. This amounts to a solar fraction of 36%. The same solar fraction of 36% is obtained by delivering 714 MWh/year to the heat consumer 1. The DH net (heat consumer 3) is supplied with only a very small amount of solar energy in this case.

3.2.2. System assessment and optimization

Although some of the conditions at RAG facilities are fixed, the boundaries of the system allow different technical solutions to be applied. Taken as “reference case” the preliminary design above described, comprehensive TRNSYS simulations have been carried out to assist the design and optimization of the system.

An interesting possibility to improve the system performance is to reduce the solar set point temperature. This set point temperature is reached by control of the primary and secondary solar circuit massflows in such a way that – depending in the solar irradiation and the temperature level in the lower part of the water storage – the collector field delivers this temperature. By reducing it, the mean operation temperature of the collectors is decreasing with the effect that the operation efficiency of the collectors is increasing. This is, however, usually restricted by the load side. Lower temperatures improve the solar efficiency but a lower temperature heat is as well provided. In our case under study the highest temperature is required by the DH network (90-100ºC of supply temperature required, while the return flow temperature varies between 70-80ºC). The reduction of the solar set point temperature below the supply temperature of the DH network is however possible due to a change in the operation strategy: instead of heat delivery at supply temperature, the integration of the solar system can be designed in such a way that the return flow of the net can be preheated by solar thermal heat. This effect results in a solar net gain of 344kWh/m^2 what is 11% more than the reference case (*Figure 35*).

In order to maximize the solar net gain the integration of Seasonal Thermal Energy Storage (STES) concept has been analysed. RAG owns four oil tanks of 60.000m^3 each. Currently a discussion is taking place regarding the use of one of them. Due to this situation, three alternatives are conceptually feasible for the integration of the STES concept into the system:

a) To build a new STES in the surroundings in case the four oil tanks have to be used for oil storage

b) To reconvert one of the oil tanks that will not be longer used for oil storage into a STES (60.000m^3)

c) Overheating of the oil tanks as an extension of the seasonal concept: surplus solar heat in summer months is used to heat the oil up to 30ºC (higher than the 25ºC reached at present) enabling a higher amount of solar energy that can be stored in the oil tanks seasonally and thus reducing the fossil fuels consumption in winter time.

The plot of land that was made available for the demonstration plant will fully be used by the solar thermal plant to place the collectors, thus there is no sufficient space to realize a new STES and therefore the alternative a) is disregarded.

Concerning the other two variants, the following *Figure 36* and *Figure 37* show an overview of the energy flows obtained for each alternative from simulations.

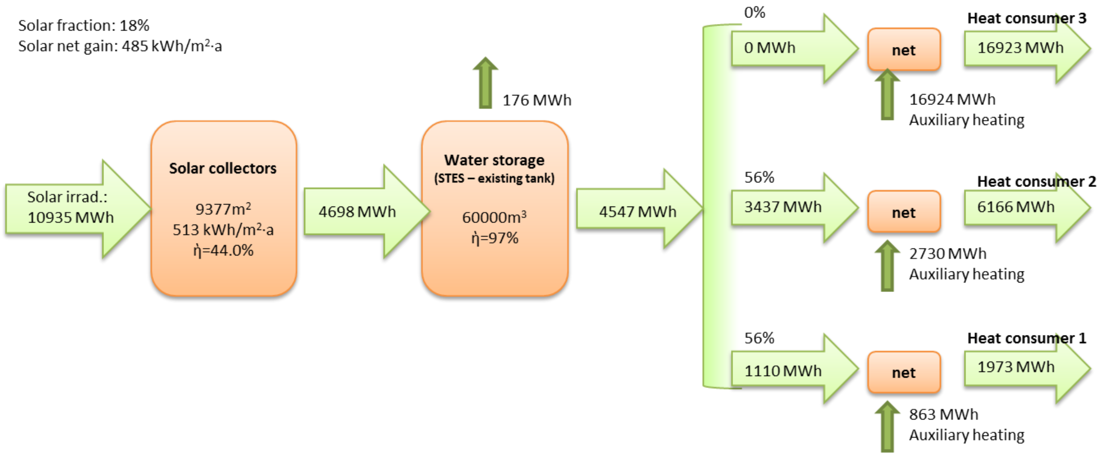

Figure 36. Simulation results for variant "b) Reconversion of one of the oil tanks into a STES". Solar system heat balance including a STES with 60.000m3 (one of the existing tanks) and reduced set point temperatures for the collector circuit. Datasource: Solites, Grafics: Tecnalia

Realizing a STES enables the entire system to store a lot of solar energy through summer to use it for low-temperature heating purpose in winter. The system layout asks for mean operation temperatures in the collector field that are so low that the yearly solar net gain rises to 485 kWh/m^2 even the STES has higher heat losses than the 300m^3 water storage. However, the impressive high solar net gain can be obtained by focusing the solar energy on the heat sinks with the lowest temperatures. As it can be seen in *Figure 36*, for this variant no solar energy is fed into the DH net to avoid the high supply temperatures this heat sink asks for. Thanks to the STES for the two other loads a solar fraction of 56% of their yearly energy demand can be obtained.

On the other hand, the other variant above mentioned has been as well analysed (variant c) overheating of the four oil tanks). *Figure 37* shows the simulation results regarding this alternative. (It should be mentioned that in this case "heat consumer 2" is addressed by heating the oil tanks).

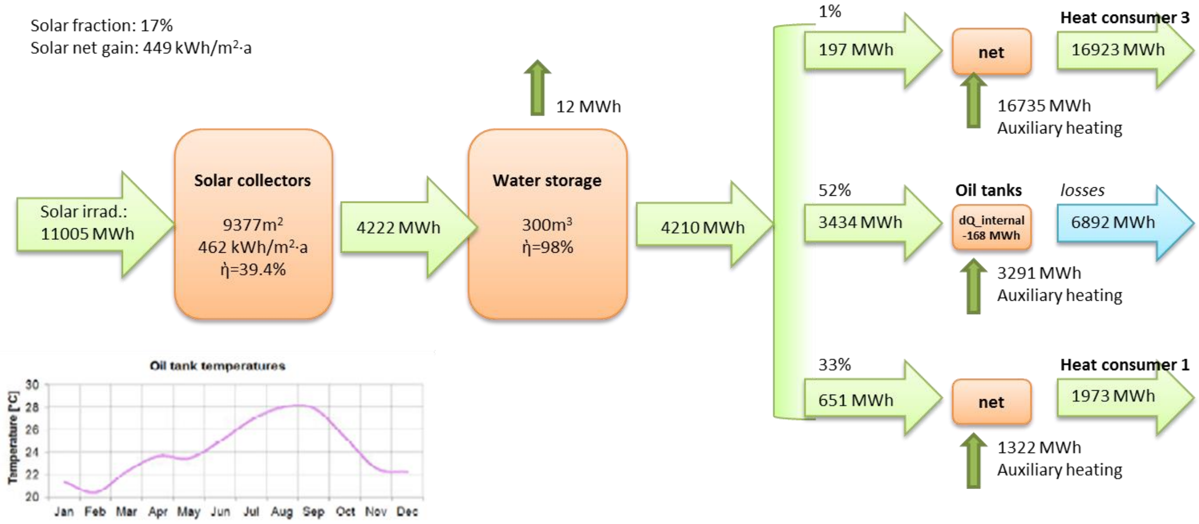

Figure 37. Simulation results for variant "c) Overheating of the oil tanks". Solar system heat balance with oil tanks set temperatures 20-30ºC and reduced set point temperatures for the collector circuit. Datasource: Solites, Grafics: Tecnalia

According to the obtained favourable results, there is no doubt that it could be as well a very good alternative in case the four oil tanks must be used for oil storage and the reconversion of one of the oil tanks into a STES is not feasible. Increasing the set temperature of the oil tanks to 30ºC, the main results as shown in *Figure 37* are that the solar net energy gain rises impressively to 449kWh/m^2 with the effect that there is only very few solar energy left that is delivered to the DH net where a solar heat delivery of only 197MWh remains.

Finally, as said above, being solar heat delivery to the DH net one of the purposes of the plant, to heighten the amount of heat delivered to the net has been analysed. Due to the high temperatures that this sink requires compared to the other loads the heat delivery to the DH net has a direct impact on the system efficiency (and therefore also in the economics). From technical point of view, to heighten the amount of heat delivered to the net is possible. The control strategy can be adapted so that heat delivery to low temperature loads is avoided to deliver much solar thermal energy to the DH net. Because the load of the net during summer is quiet low, in parallel the heating of the other loads is kept open for solar thermal supply. Without adapting the control strategy as just mentioned, the heat delivered to the DH net was insignificant; with this control strategy that priorizes the heat delivery to the net and increasing the buffer storage to 600m^3 to avoid very high temperatures in the tank during long periods that reduces the solar efficiency significantly, a specific solar net gain of 264 kWh/m^2 and 5% of solar fraction could be obtained (874 MWh delivered to the net).

The discussion of these results among the involved entities led to the conclusion that the reconversion of one of the existing oil tanks into STES was a very interesting alternative for the present project, which addressed to the next step of developing a technical solution for the reconversion of the existing tank.

3.3. RECONVERSION OF EXISTING OIL TANK INTO STES

According to the results shown in previous chapters it is clear that the system performance increases significantly if seasonal storage of solar energy can be integrated within the system concept. Reconversion of one of the existing oil tanks into STES may be a promising solution. Investigations have been carried out to develop an oil-to-water reconversion solution that is technically and economically feasible for the existing oil tanks at RAG.

An important detail of the existing tank under consideration is related with its roof: the lid integrates a pontoon on the outer circle that enables the roof to flow on the oil (*Figure 38*). The lid was built so that it can go up and down inside the wall cylinder when the oil is charged and discharged. The floating principle is not necessary when using the tank for STES purposes, but it is a characteristic to be seriously considered when developing the reconversion solution as this can cause quite problematic difficulties.

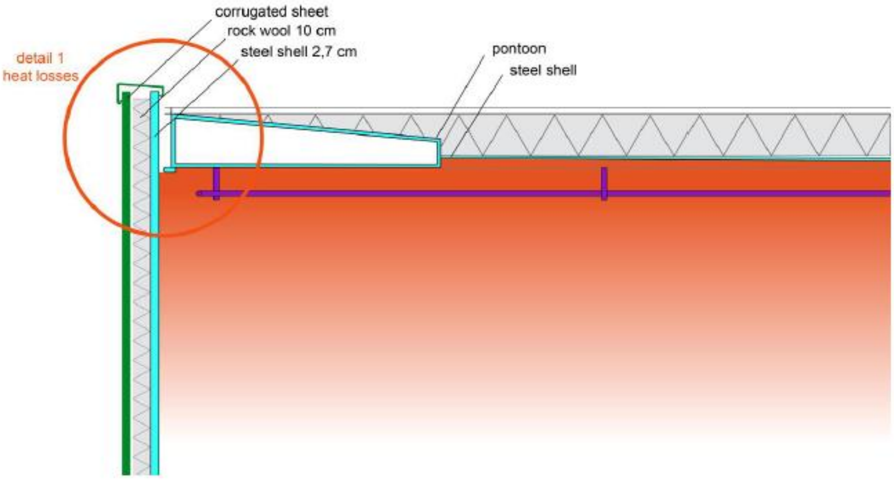

Figure 38. Detail 1: Gap between tank all and floating pontoon lid. Source: Solites.

Figure 39. Envelope of the existing oil tank at RAG and its heat insulation. Source: RAG.

Heat insulation needs have been specifically analyzed. While the initial use of the tanks for oil storage means to work at around 20-25ºC (not too far from ambient temperature), the new application as STES implies to work at much higher temperatures, up to 80ºC to 90ºC on the top. Whether the existing heat insulation level is appropriate or not has been therefore specifically analyzed.

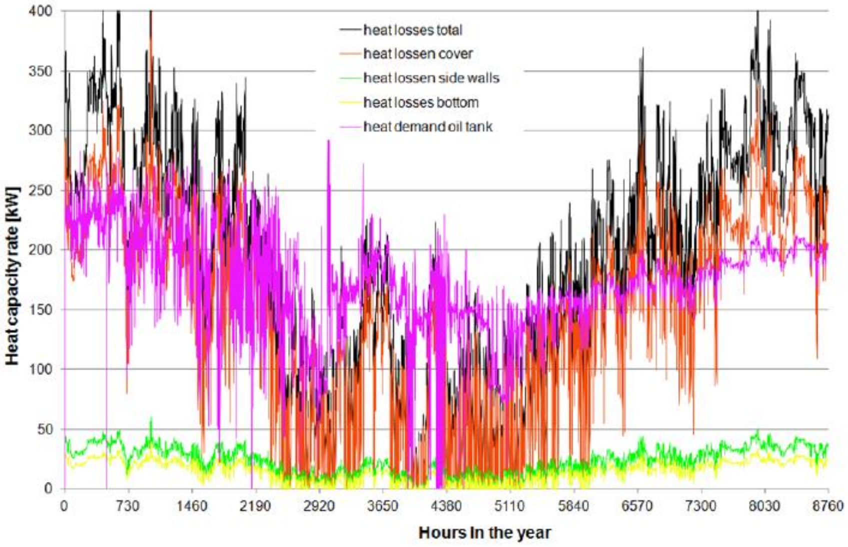

Figure 22: Heat losses over one year of the existing oil tanks simulated with TRNSYS (source: Solites)

Figure 40. Heat losses over one year of the existing oil tanks simulated with TRNSYS. Source: Solites.

Simulations carried out have shown that the heat losses within the tanks are very high: most of the additional energy that would feed in the STES would be lost until the winter by heat losses. It has been clearly observed that these heat losses are mainly given through the not insulated cover (Figure 40). An additional heat insulation of the wall of the STES of course reduces the heat losses through the wall, but in comparison to the overall heat losses this improvement would have a quite small impact on the total heat losses. The technical and economical effort would be very high, thus this possibility could directly be excluded. However, to add a heat insulation of the top of the STES is highly recommended: insulating the lid would improve the energy balance of the STES to a very high extend. Nevertheless, an appropriate way has to be found to minimize the expenses and avoid making it economically unfeasible.

If adding insulation to the cover is economically interesting mainly depends on the realization possibilities. The challenge in this particular case is related to the lid that is swimming on the oil level without close connection to the walls. For heat insulation of the lid it has to be connected in the best way water vapour diffusion tight to the walls that no water vapour can diffuse into the heat insulation. This might reduce the insulation capabilities of the insulation material considerably. First economic estimations show that if scaffolding of the entire storage is necessary for performing the work, only the assumed cost for this scaffold are so high that the entire idea of adding heat insulation to the lid runs in diseconomies. Adding heat insulation to the lid is therefore recommended but an economically feasible solution must be found.

One of the most important issues when considering the reconversion of an existing tank into a STES is to check if the detailed construction and statics of the existing tank fits to a usage as a STES. When using the tank as a STES, the water inside the STES will stratify so that high temperatures are on top and the lowest ones on the bottom. This leads to static stress especially on the tank walls because the top parts will be on a higher temperature than the lower parts. The temperature lengthening of steel with rising temperature will cause static stress for the wall construction. It has to be proven that the entire storage construction can withstand that temperature stress on a long-term. A detailed statical calculation has to be carried out to prove the suitability of the existing tank construction to be used as a STES according the existing EU building standards.

In addition to the static stress that may be occurred due to water stratification inside the tank when working as a STES, the particular construction of the tank under study has an additional challenge to be overcome, which is related to the floating lid. The existence of a gap between the tank wall and the lid can cause quite problematic difficulties when working as a STES, in addition to the heat and water vapour losses through the open gap.

When the tank construction is heated for STES purposes, the steel in the wall and in the lid will expand due to the temperature lengthening of the steel material. Due to the large diameter of the lid it might occur that the lid will expand to such a high extend that it become stuch in the inner wall clinder. This might cause static hazard to the lid or/and the wall. In addition to the expansion of the lid, it might occur that the cylinder of the wall gets deformed by the temperature stratification about its height. The effects of deformation depend on the quality of the weldings that were performed when realizing the tank, the corrosion since that time, etc. These effects cannot be calculated and consequently no secure statement to the functioning of a floating lid on a STES made of an old oil tank can be developed. The only feasible alternative that has been concluded therefore for this specific case so that the tank can be used as STES is to fix the lid on top of the storage volume.

Any option that requested a scaffolding of the storage volume has been discarded. The costs for such scaffolding are so high that they would be too expensive. The costs for this scaffolding are very high because the volume to be scaffolded is very huge, the mounting of the scaffold is quite difficult because the single parts of the scaffold has to be brought into the tank through the manhole or smaller hole in the lid, etc.

The following *Figure 41* shows the best solution for the reconversion of the tank under study.

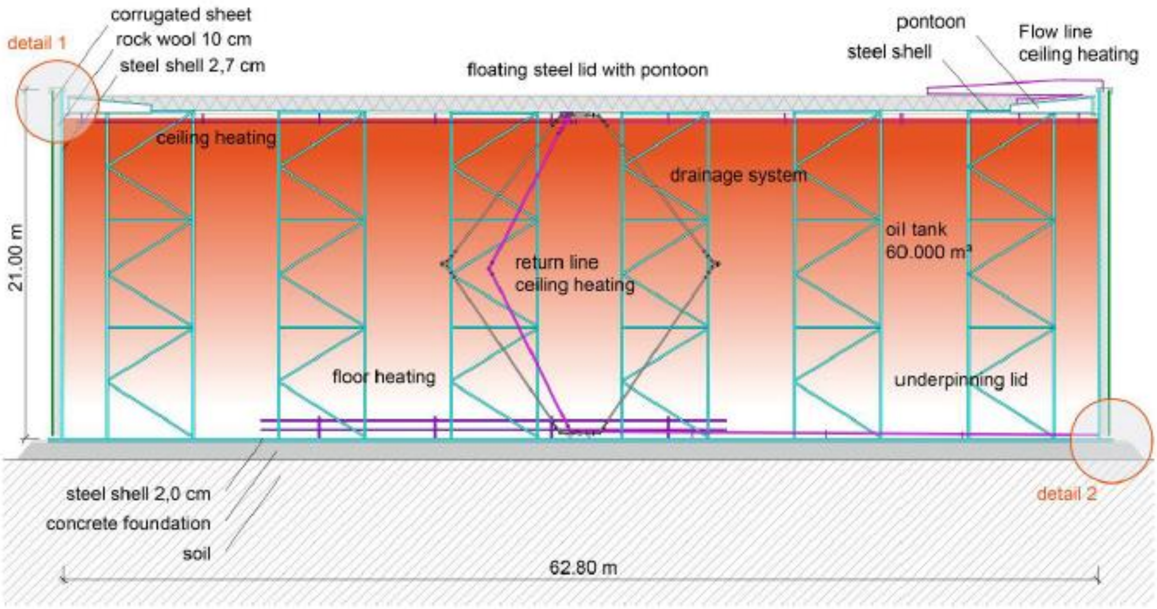

Figure 41. Reconversion solution for the existing tank of 60,000m3 to be used as STES. Source: Solites.

A simple prolongation of the existing underpinning is not possible because they are too thin compared to the end height for avoiding possible buckles. But if the single underpinnings would be connected to each other to realize a kind of a vertical trussed girder, the construction would be very cost effective and easy to realize. The lid that rests on its underpinnings would be lifted step by step by hydraulic lifts that are mounted inside the tank. With every step the next part of the trussed underpinnings can be mounted. Because the trussed underpinnings consist of small steel beams, it is quite easy to transport them inside the tank. These steel beams for realizing the trussed underpinnings can be prefabricated totally, the mounting can be done by screws, welding o.e. Step by step the lid will be lifted by the hydraulic lifts with the trussed underpinnings growing into the inner height until the end height is reached. No scaffold is necessary and the amount of steel that is needed for the construction is minimized, due to the fact that the carrying construction is trussed. After that the roof can be heat insulated and closed by a watertight plastic liner.

The work described in this section has shown that the reconversion of existing tanks for STES applications may be feasible. Based on the work performed for the specific project at Kremsmünster and particular boundary conditions of the existing tanks at the oil and gas facility owned by RAG, most important challenges to be addressed have been explained. Although each reconversion project will undoubtedly have particular features, the following issues should be always in mind:

- Proof of the static calculations if the storage construction can be heated as STES (with temperature stratification that leads to static stress on the tank walls). A detailed statical calculation has to be carried out to prove the suitability of the existing tank construction to be used as a STES according the existing EU building standards.
- Cleaning of the storage, of all pipes, etc from raw oil
- Solution for corrosion protection of the inner steel surfaces that might be caused by the filled-in water. One solution can be to use pretreated water that’s oxygen content was eliminated before filling.
- Investigation if additional heat insulation is advisable by energetic and/or economic reasons.

3.4. SELECTION OF BEST SOLAR COLLECTOR TYPE BASED ON FIELD TESTS

In addition to the system concept optimization, the use of most efficient solar collectors is also crucial in order to maximize the solar net gain.

A test field in the city of Graz with a collector field of 2.480m^2 has been built and the collector efficiency of several different collector types of different collector manufacturers has been tested under real outside conditions. It is well known from the experience of PITAGORAS partners that the performance of a collector in field operation derives a lot from the single collector test under labour test conditions. Also SOLAR KEYMARK certified collectors do not perform in field as they perform under test conditions. These tests have provided therefore very valuable insights not only to choose the most efficient collector for the plant to be developed, but also for future development of solar collectors.

Five different collector types from four different collector manufacturers have been tested under the same conditions. The tests are running since summer 2014. The overall size of the collector field is 2.480m^2 and each collector type is assembled in 200-500m^2 area. All collectors are measured separately and feed directly in the district heat network of Graz.

Figure 42. Aerial view of test field. Source: Solid.

The obtained results show important differences between the different collectors' performances. The following table shows the specific annual solar yield of the different collector fields tested:

Tabla 5. ***Specific annual solar yield***

Specific annual solar yield in kWh/m^2				
Collector nº1	Collector nº2	Collector nº3	Collector nº4	Collector nº5
394.97	457.99	406.07	290.21 (*)	503.09

** It should be noted that the collector field nº4 has been installed in May 2014 and the first full month of operation was in June, so there are no results over the whole year for this collector field.*

In the following figure the monthly solar yield of each collector type from October 2014 until September 2015 is shown.

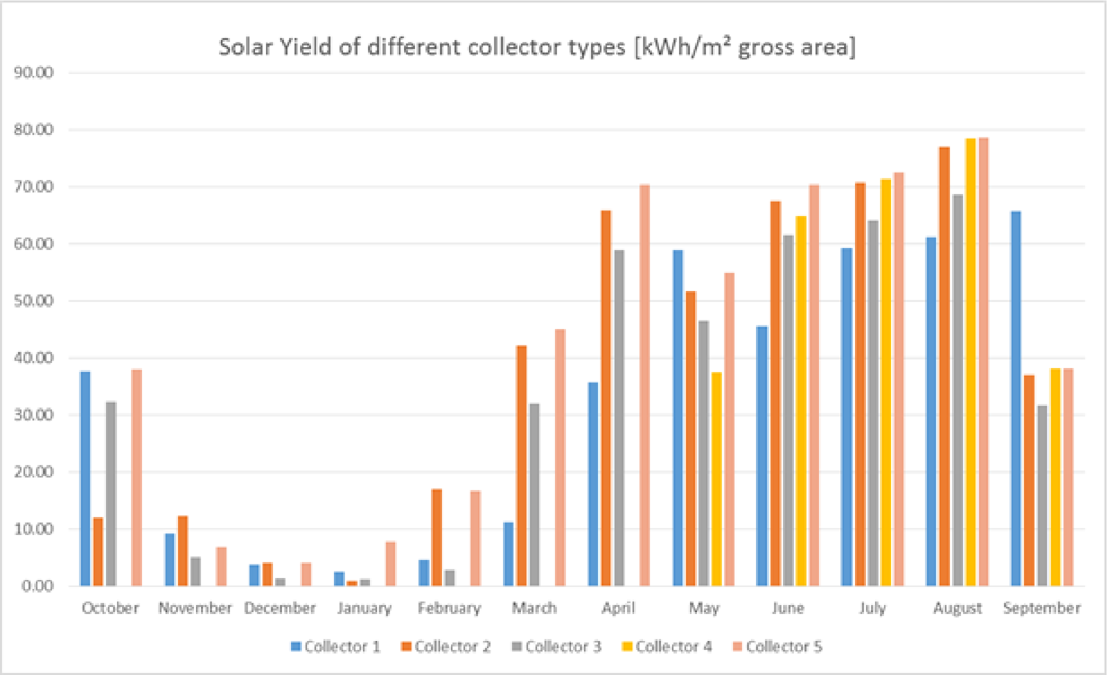

Figure 43. Monthly solar yield of the different solar collector fields tested. Source: Solid

It has been observed that this deviation is much more prominent in a sunny day in wintertime than in a typical sunny day in summer.

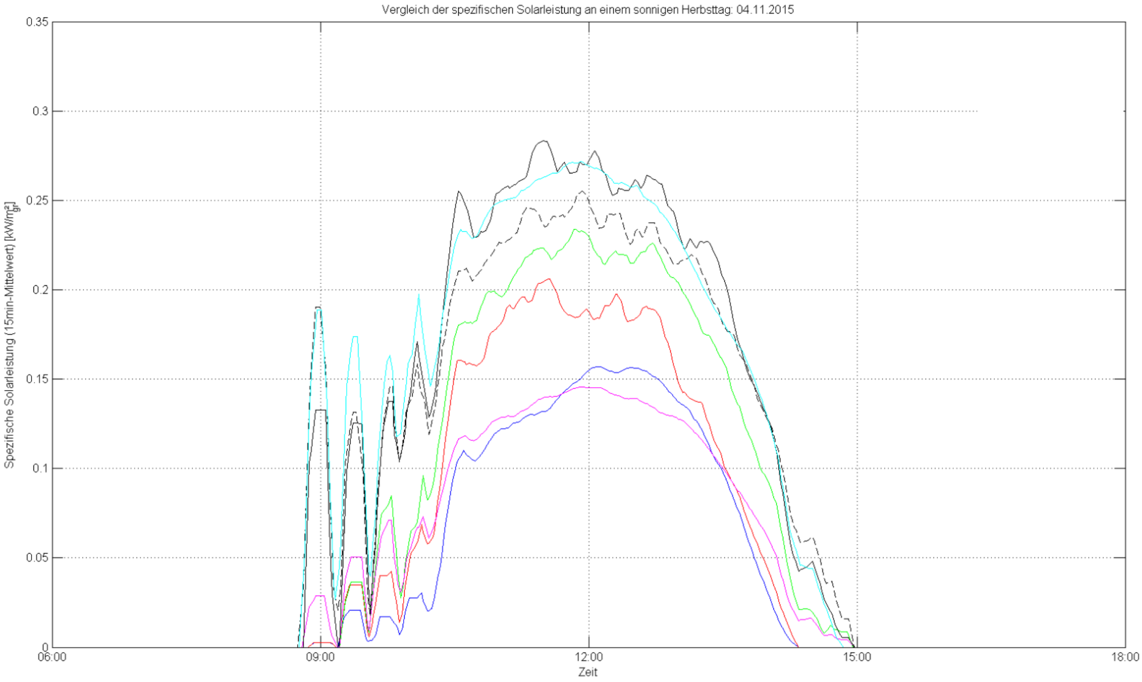

Figure 44. Specific daily solar yield (sunny day in November, 04.11.2015). Source: Solid.

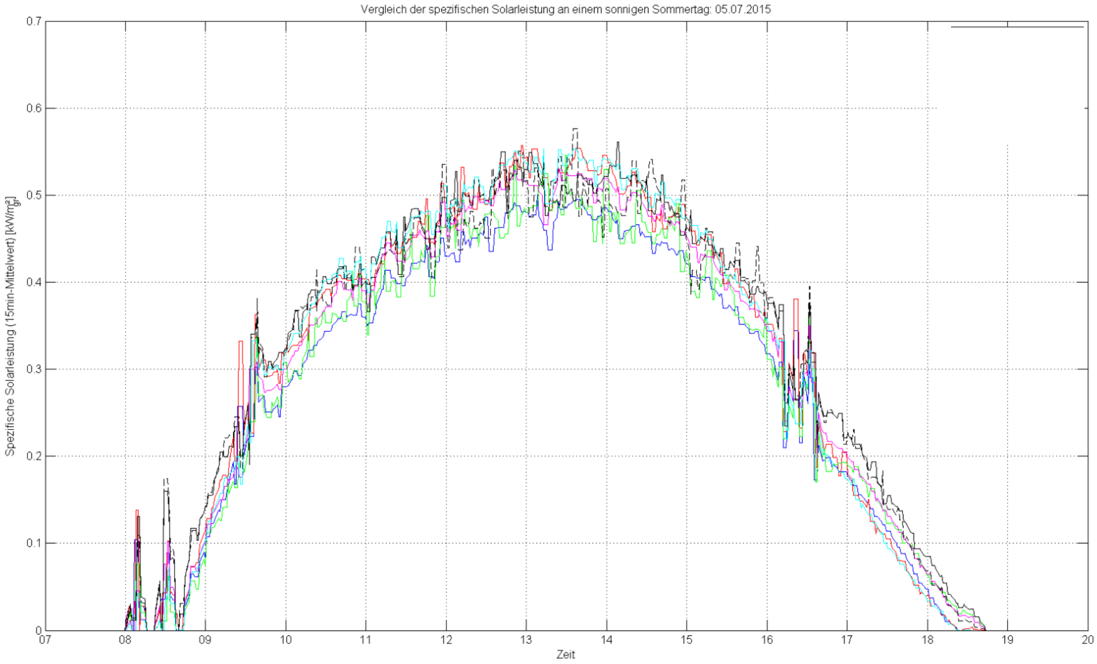

Figure 45. Specific daily solar yield (sunny day in July, 05.07.2015). Source: Solid.

The first results that have been analysed highlight the importance of selecting appropriately the solar collector, showing that there may be significant differences between them. In addition, it is worth to mention that the performance of the collectors is roughly 10% less on average than outlined in the Solar Keymark Certificate.

Among the tested collectors, the Collector nº5 seems to be the most attractive for the implementation of the Kremsmünster plant with a solar yield of 503 kWh/m^2 under the test conditions.

Finally, it should be noted that this section reflects an on-going work. First conclusions are shown in the present report. However, further results and conclusions will be disseminated accordingly in future reports and publications.

4. CONCLUSIONS

This report is a deliverable of the European funded PITAGORAS project “Sustainable Urban Planning with innovative and low energy thermal and power generation from residua and renewable sources”. The overall objective of the project is the development of highly replicable, cost-effective and high-energy efficiency large scale energy generation systems that will allow sustainable urban planning of very low energy city districts.

Specifically the PITAGORAS project works on the development of two pilot plants: one in Brescia (Italy) and a second one in Kremsmünster (Austria). The present documents presents a comprehensive description of the work performed in the design phase of these two plants.

The system developed for Brescia is a waste heat recovery solution coupled with an ORC unit. Waste heat recovery takes place in a still mill factory and steam is generated in a WHRU which is used to feed the ORC unit for electricity production or the heat exchangers that supply heat to the city DH network.

The potential for waste heat recovery is estimated in $10MW_{th}$ approximately and it is expected to produce around 52.000MWh of usable waste heat from the flue gases that are available at an average temperature of 500ºC and will be cooled down until approximately 210ºC after the exchange. According to the system sizing, an ORC unit of 1,8MWe has been selected, which is expected to produce around 4.200MWh of electricity that will be used for self-consumption. The plant has been designed for a total heat delivery capacity of $10MW_{th}$ and around 26.500MWh of district heat is expected to be delivered to the city DH network that operates at supply and return flow temperatures of 95-120ºC and 60-85ºC, respectively.

The pilot plant that has been designed for Kremsmünster is based on the use of solar thermal energy. The developed solution combines the solar heat supply to an oil and gas industry for covering internal loads together with the heat supply to the city DH network in order to increase the renewable fraction of the network. In order to maximize the solar yield and in consequence the economics of the system, STES concept has been integrated into the system concept. The developed work shows a solution for the reconversion of an existing tank (that was commonly used for oil storage) into a STES, demonstrating that a technical and economically feasible way can be found for such innovative integration solutions.

In order to fulfil the objectives regarding the coverage of the heat loads, a solar collector field of $9.377m^2$ has been concluded as necessary. The existing tank to be used as STES has a storage volume of $60.000m^3$. This would allow producing 4.547MWh of solar heat to be delivered to the different heat loads. The expected solar net gain is 485 kWh/m^2 and it would be possible to achieve a solar fraction of 56% in the coverage of the internal heat loads of the oil and gas company.

5. REFERENCES

A. Saltelli, S. T. (2000). Sensitivity analysis as an ingredient of modelling. *Statistical Science*, Vol.15, No4, 377-395.

Deliverable 2.1. System concept assessment of the whole system for the two demonstration plants. PITAGORAS project.

Deliverable 2.3. Organic Rankine Cycle system conceptual design. PITAGORAS project.

Deliverable 2.10. Organic Rankine Cycle system detailed design. PITAGORAS project.

Deliverable 2.13. Guidelines for optimization of the integration of the Pitagoras plant concepts with the DH network

Klein, S. e. (2010). *TRNSYS 17: A Transient System Simulation Program.* Madison, USA: Solar Energy Laboratory, University of Wisconsin.

ANNEX I: SUMMARY OF EUROSTAT ENERGY PRICES AND ELECTRICITY EMISSION FACTORS ASSUMED IN THE STUDY

Tabla 6: Summary of Eurostat energy prices and electricity emission factors assumed in the study

City	Country	Gas price	Electricity price	Electricity to CO_2 emissions conversion factor
[-]	[-]	[€/kWh]	[€/kWh]	[kg/kWh]
Athens	Greece	0.0467	0.1298	0.7224
Barcelona	Spain	0.0374	0.1167	0.2988
Belgrade	Serbia	0.0383	0.0666	0.6803
Bergen	Norway	0.0441	0.0808	0.0172
Berlin	Germany	0.0401	0.1520	0.4305
Bilbao	Spain	0.0374	0.1167	0.2988
Brescia	Italy	0.0345	0.1735	0.3864
Graz	Austria	0.0401	0.1055	0.1632
Madrid	Spain	0.0374	0.1167	0.2898
Marseille	France	0.0379	0.0908	0.0898
Porto	Portugal	0.0474	0.1187	0.3682
Prague	Czech Republic	0.0304	0.0819	0.5142
Rome	Italy	0.0345	0.1735	0.3864
Stuttgart	Germany	0.0401	0.1520	0.4305
Warsaw	Poland	0.0364	0.0833	0.6402