SMART DUAL THERMAL NETWORK

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ABSTRACT

Conventional district heating (DH) systems enable demand aggregation at district level and can provide high centralized heat generation performance values. However, thermal Renewable Energy Sources (RES) deployment at building level still remains low, and exploitation suboptimal, as it is limited by the instantaneous thermal load and storage capacity availability of each building. Buildings play the role of consumers that request a variable amount of heat over time and the thermal network the role of unidirectional heat supplier, without any smart interaction. The FP7 project A2PBEER has developed an innovative Smart Dual Thermal Network concept based on RES and Combined Heat and Power (CHP) as generation technologies, that enables transforming existing suboptimal DH systems, into integrated thermal networks with optimized performance and building level RES system production exploitation. It is based on an innovative Smart Dual Building Thermal Substation concept, which allows a bidirectional heat exchange of the buildings with the thermal network, and to aggregate district level distributed production and storage capacity (Virtual District Plant). With this approach buildings become prosumers maximizing decentralized RES production exploitation, as any possible local heat production surplus on any building of the district, will be delivered to the network to be used by other buildings. Additionally, this thermal network allows the delivery of the energy necessary to meet the heating and cooling demand of the buildings through a single hot water distribution network. In this way, it is possible to upgrade conventional DH systems to district heating and cooling systems, without the construction of a district cooling plant and a dedicated cooling distribution network. Cooling is produced at building level through sorption technologies using locally deployed solar collectors and the thermal network as energy sources. Finally, the district typologies and climatic conditions that maximize the potential of this thermal network concept have been identified.

Keywords: District heating, district cooling, distributed generation, smart grids, thermal substations.

1 INTRODUCTION

Conventional district heating (DH) systems enable demand aggregation at district level and, under appropriate technical and economical boundary conditions, can provide high centralized heat generation performance values and minimize the required aggregated generation capacity. Additionally, these systems offer the possibility to integrate very efficient generation technologies such as Combined Heat and Power (CHP). However, thermal Renewable Energy Sources (RES) deployment at building level still remains low, and exploitation suboptimal, as it is limited by the instantaneous thermal load and storage capacity availability of each building.

District heating solutions are common in many northern European countries with cold climatic conditions. However, district cooling systems even in countries with very hot climatic conditions that set the ideal frame to take full advantage of them, are not a usual approach. Instead, cooling generation is solved at building level through conventional compression chillers and reversible heat pumps.

The interaction between buildings and the thermal network is established by a strict hierarchy where buildings play the role of consumers of heat delivered at some specific conditions (temperature and pressure), and the district heating the role of unidirectional heat supplier connected through heating substations designed to enable such heat interaction. Thermal networks are managed according to reactive control strategies focused on adapting the status

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of the system (plant generators, storage systems, pums, etc) to the evolving district demand, so that the supply temperature and pressure setpoints are met over time.

On the other hand, district heating and cooling systems are very unusual and, from a technical point of view, based on the deployment of dedicated heating and cooling plants and of specific distribution networks for heating and for cooling (4 pipe distribution systems). According to traditional approaches, the transition from currently existing district heating systems to advanced heating and cooling systems requires the installation of a district cooling plant and the deployment of a dedicated cooling distribution network. However, this approach must face huge technical and economic obstacles, as it requires a complicated construction process, with a strong impact on the exploitation of the buildings of the district and inconveniencies for building users for prolonged periods.

The objective of this study is to develop the innovative Smart Dual Thermal Network concept (SDTN) and the Smart Dual Building Thermal Substation, which is the key component to enable the implementation of the proposed concept. This innovative thermal network is based on RES and CHP as generation technologies, and aims at transforming existing suboptimal public DH systems, into heating and cooling thermal networks with optimized performance and building level RES system production exploitation, avoiding the limitations currently existing in traditional DH system upgrading procedures.

The Smart Dual Building Thermal Substation (SDBTS) allows a bidirectional heat exchange of the buildings with the thermal network, and to aggregate district level distributed production and storage capacity (Virtual District Plant). With this approach buildings become prosumers maximizing decentralized RES production exploitation, as any possible local heat production surplus on any building of the district, will be delivered to the network to be used by other buildings.

2 SMART DUAL THERMAL NETWORK CONCEPT (SDTN)

2.1 Smart Network. Bidirectional heat exchange.

Generally speaking, public districts will be formed by buildings with different usage characteristics and different potential for integration of solar thermal collectors and CHP units. Some buildings will operate on a yearly basis (office buildings, etc) while others might remain without any activity for prolonged periods (educational buildings during summer, etc), and the same differences could exist on a daily basis, as some buildings will remain occupied during working hours while others will only be occupied during nights.

Additionally, the characteristics of the energy demands of the buildings might also be very different in relation to the distribution on a daily and yearly basis, and also regarding the relative weight corresponding to heating, Domestic Hot Water (DHW) production and cooling. On the other hand, due to the architectonic features of the buildings (availability of roof space to deploy solar collectors, shading effects, etc) the RES deployment potential of each building might be very different.

Bidirectional heat exchange through Smart Dual Thermal Substation deployment, will enable the aggregation of the distributed solar collector, CHP and storage systems creating a Virtual District Plant that will allow taking advantage of possible synergies between the usage and the heat generation profiles of the different buildings, reducing the required capacities, improving generation efficiency, and increasing the operation intensity of the CHP units of the Virtual District Plant.

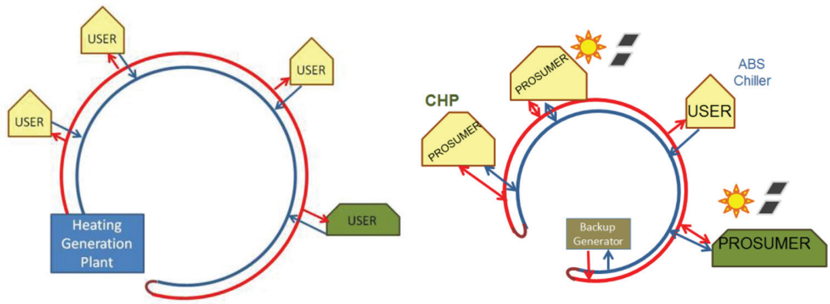

Figure 1: Conventional and innovative networks.

2.2 Dual Thermal Network

Additionally, this thermal network allows the delivery of the energy necessary to meet the heating and cooling demand of the buildings through a single hot water distribution network. In this way, it is possible to upgrade conventional DH systems to district heating and cooling systems, without the construction of a district cooling plant and a dedicated cooling distribution network. Cooling is produced at building level through conventional or innovative sorption technologies using locally deployed solar collectors and the thermal network as energy sources.

An innovative triple state sorption technology integrated into solar collectors has been developed by ClimateWell AB in the frame of the FP7 project A2PBEER, in order to provide this functionality. This collector can provide hot water (up to 95°C) operating in heating mode, and cool water (7°C) and low temperature hot water as a byproduct (35–45°C) operating in cooling mode [1]. In any case, conventional absorption chillers can also provide building level cooling production.

The nominal performance of conventional single effect absorption technologies is typically around 0.8, whereas for conventional compression based technologies higher performance values (2–6) can be obtained depending on the selected specific technology. Therefore, in order to make use of absorption as cooling generation technology in a competitive way in terms of efficiency and costs, the heat supply to absorption components is based on generation technologies that can provide free heat such as solar collectors, and technologies with very high economic performance such as CHP (when the cost of electricity is much higher than natural gas and other fossil fuels and biomass).

2.3 Integrated District Energy Management system based on model predictive control strategies.

In order to operate thermal networks as optimized integrated systems it is necessary to evolve from traditional reactive control approaches to a model predictive control approach [2]. Therefore, ICT management platform and energy model integration will be required.

The platform architecture must enable interoperability between building and district level energy management systems through standard communication protocols. This enables operating building level systems (CHP plants) according to district level constraints.

The developed framework is formed by a cluster of Building Supervisory Systems coupled to a District Supervisory System that will act as master. These systems are installed, respectively, on top of the existing Building Energy Management Systems (BEMS-s) and the district

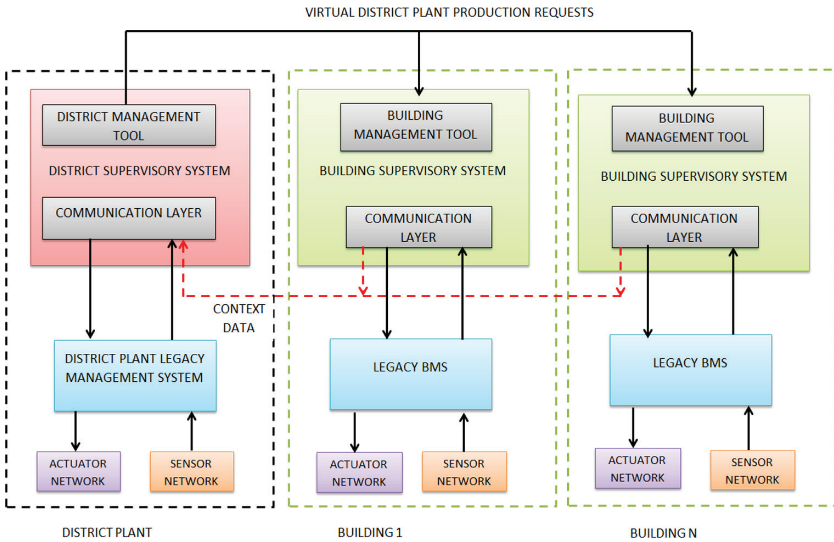

Figure 2: Architecture of the integrated district management system.

management system, and have the capacity to disseminate the required control commands to implement the optimized operational strategies at building and thermal network level.

2.4 Transition procedure

The thermal network concept has been developed for already existing public DH systems. Therefore, a flexible transition procedure that can be gradually implemented over time according to the technical constraints and economic availability of each specific project has been defined.

If the district heating plant is not based on CHP and RES, the process will consist in the gradual substitution of the existing heat generators, as they reach the end of their live span. In many cases, according to the existing specific constraints, the deployment of CHP will not take place at district plant level, but at Virtual District Plant level. The Virtual District Plant will be completed with the deployment of solar collectors at building level. Aggregation of distributed generation systems will increase the available flexibility to carry out the transition to the advanced thermal network concept. It is necessary to take into account that under many technical and economic circumstances, it might be easier to enable many small scale interventions distributed over several of the buildings connected to the network than big scale interventions at district heating plant level.

The transition procedure will be completed with the deployment of the Smart Dual Thermal Substation on the buildings of the district.

2.5 Technical and economic boundary conditions for district retrofitting through the SDTN

For the complete implementation of the SDTN concept the following technical and economic conditions must be fulfilled:

- Presence of relevant aggregated heating and cooling demands.
- The district should be formed by buildings with complementary energy use and local production patterns.

– Adequate balance between fuel and electricity prices.
– Favorable regulations regarding distributed production (feed in tariffs).
– Availability of an integrated district energy management system operating according to model predictive control strategies.

If not all these requirements are met, partial thermal network implementations will still be possible:

– The Smart Thermal Network (STN), including only the bidirectional heat exchange functionality (absence of cooling or unfavorable balance between fuel and electricity prices).
– The Dual Thermal Network (DTN) including only the dual nature of the network (absence of synergies between the demand and production profiles of the buildings of the district).

3 SMART DUAL THERMAL SUBSTATION

3.1 State of the art heating substations

A typical building heating substation has to fulfill several requirements, in order to ensure a satisfactory delivery of the required functionalities from the perspective of the consumer and the utility managers. An overview of such requirements is provided in Table 1.

In general, a building heating substation must provide energy to meet the needs of local heating systems and DHW production. The most usual substation types are the parallel systems and the 2 stage systems, in both cases with the possibility to incorporate a charging tank or instantaneous DHW production.

Parallel substations include specific heat exchangers for DHW production and for the heating system, connected in parallel to the thermal network. The 2 stage arrangement is more adequate for systems with a large DHW demand where the primary return flow of the heat exchanger of the heating system is used in the first stage of the DHW heat exchanger to preheat the makeup cold water. The temperature of the DHW is raised to the required level in the second stage of the DHW heat exchanger with hot water supply from the primary circuit of the thermal network. With this approach the return water temperature of the primary side of the DH is lowered further [3].

3.2 Smart Dual Thermal Substation functionalities, modules and typologies

The building thermal substation is the key component to transform existing traditional thermal networks into the developed advanced thermal network concept. Table 2 displays the required functionalities and modules.

Table 1: Conventional heating substation functional requirements.

General	Consumers	Utility managers
Accurate and stable temperature control	Sufficient supply temperature	Preferably indirect connection through heat exchangers
Low risk of bacteria growth	Low energy consumption	Low return temperature
Safe function	Accurate heat metering	Maximum flow limitation
Minimum space demand	Low noise level	Easy maintenance
Long operational life	Low cost	Sufficient differential pressure

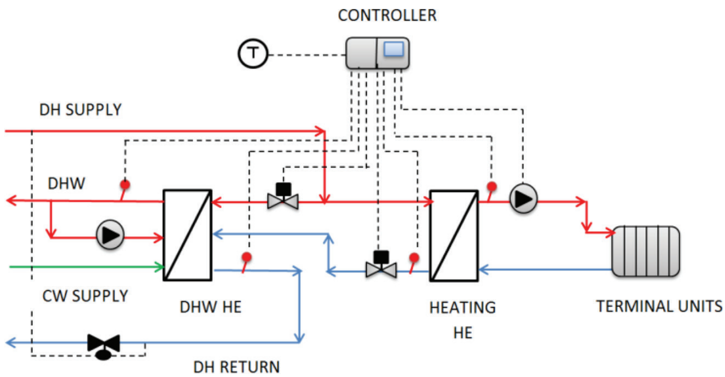

Figure 3: Two stage heating substation with instantaneous DHW production.

Table 2: Innovative thermal substation functionalities and modules.

Functionality	Description	Involved module
Heating	Heat delivery from the network for heating and DHW production	Heating module
Cooling	Heat delivery from the network for local cooling production through sorption components	Cooling module
Surplus delivery	Delivery of local production surplus	Surplus delivery module

According to the required functionalities and modules, the thermal substation typologies displayed in Table 3 have been defined.

Figure 4 displays the hydraulic scheme of the Dual Bidirectional Substation. As an evolution of the 2 stage arrangement used for state of the art heating substations [4], energy recovery from the outlet flow of the primary side of the cooling module is used as strategy to reduce the temperature value of the flow returned from the heating and cooling modules to the thermal network, minimizing distribution losses and improving the performance of the heat generators of the district plant.

The integration of the substation into the network is based on specific operational modes that provide the flexibility necessary to adjust the system to the requirements of all the foreseen interactions of the buildings and the network. Table 4 provides a summarized description of these operational modes, including the description of the operational settings.

Table 3: Innovative thermal substation typologies.

Typology	Functionalities	Required modules
Dual bidirectional	Heating, cooling and surplus delivery	Heating, cooling and surplus delivery
Dual unidirectional	Heating and cooling	Heating and cooling
Heating bidirectional	Heating and surplus delivery	Heating and surplus delivery

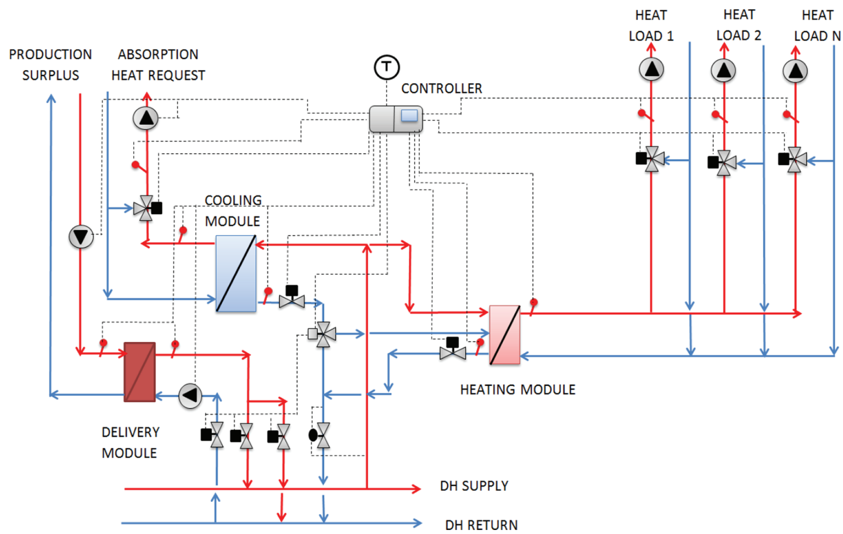

Figure 4: Smart Dual Thermal Substation hydraulic scheme

Table 4: Smart Dual Thermal Network operational modes.

Mode	Type	Functionality	Active modules	Season	Network setpoint (°C)	Surplus delivery
Heating	Network Local	Heating	Heating Delivery	Winter	65	Supply pipe (SP)
Cooling	Network Local	Cooling	Cooling Delivery	Summer	95	Return pipe (RP)
Heating and cooling	Network Local	Heating Cooling	Heating Cooling Delivery	Intermediate	95	RP
Surplus delivery	Local	Surplus delivery	Delivery	Permanently available	N.A.	SP RP

Regarding the heat delivery, two different energy delivery approaches have been defined to be activated according to the difference existing between the temperature value of the available local heat production surplus, and the temperature of the return and supply pipes of the thermal network.

If the temperature of the local heat production is higher than the supply temperature of the thermal network, the energy delivery will take place through the supply pipe (return/supply mode). However, if the temperature of the local hot water production surplus, is above the temperature of the return pipe of the network but below the network supply setpoint value, the energy delivery will take place through the return pipe (return/return delivery mode).

The return/return heat delivery mode will be less efficient, as the increase on the return temperature of the network will, in general, produce some decrease on the performance of the heat generators of the district plant, but the energy delivered to the thermal network will compensate this effect, and produce a net decrease on its fuel consumption.

4 THERMAL NETWORK ASSESSMENT METHODOLOGY

The evaluation of the potential of the SDTN is based on district dynamic behavior modelling and simulation. This is a complex goal as it involves systems affected by dynamic effects with very different time scales, contained inside space boundaries of very different scales, including technologies that are part of different domains.

Due to modelling limitations none of the existing traditional building simulation tools is suitable to meet all the requirements necessary to perform an accurate definition of a complete district in a single simulation model [5]. However, having an integrated model of the district is necessary in order to analyze it as an integrated system optimized for energy efficient operation and peak load reduction.

An offline sequential co-simulation approach has been developed [6], in order to generate the required integrated model for the district. It consists in modelling all the systems and elements included within the boundaries of each of the 3 scales, inside specific models developed in the most suitable tools, and in the definition of the procedures to couple the models, taking into account the dynamics present in the interfaces between component, building and district level models.

A key issue in relation to the implementation of the co-simulation approach is to establish the scope and boundaries of each of the models with very clear interfaces, where interaction dynamics are well known and can be accurately modeled. EnergyPlus has been selected for building and building system modeling and TRNSYS for cooling collector and thermal network modeling. Figure 5 displays the information data flows between the involved models.

In order to evaluate the potential of the SDTN, the co-simulation procedure has been applied to a virtual district heating system defined according to the following criteria:

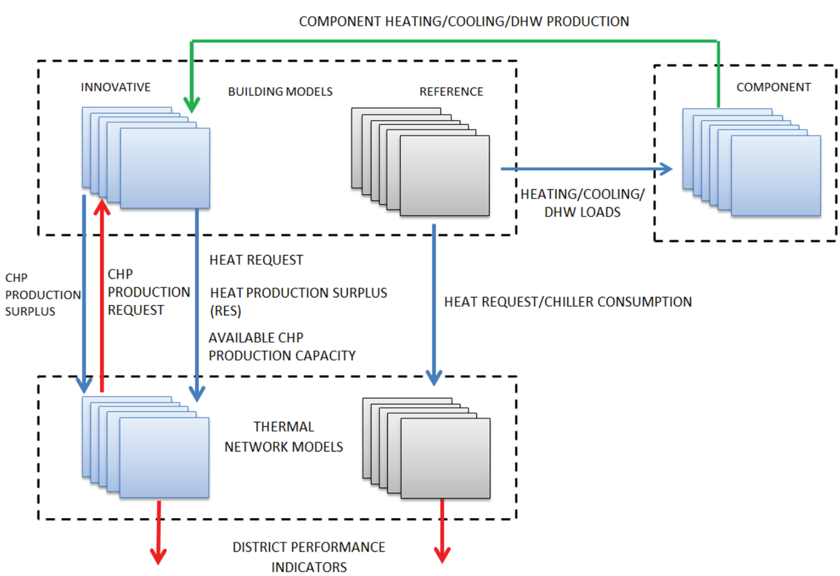

Figure 5: Co-simulation procedure architecture.

- District formed by ten buildings (2 office, 5 educational, a dormitory and 2 hotel buildings), connected to a two pipe distribution loop according to a typical topology, and with an acceptable balance between buildings that act as net consumers and buildings that act as net producers.
- District plant, formed by a CHP unit and two natural gas boilers.
- Absence of solar collectors in the reference scenario.
- Innovative sorption collector deployment on buildings with high DHW demands and conventional solar collector deployment on the rest of the buildings.
- Deployment of conventional absorption chillers on all the buildings of the district.

Starting from the reference scenario, the implementation of the innovative functionalities (bidirectional heat exchange and dual nature of the network) takes place sequentially, in order to have the possibility to evaluate the impact of each of them in a separate and a combined way. Following this approach, the obtained results can be linked with the defined thermal network typologies to estimate their specific potential (Smart Thermal Network, Dual Thermal Network and the Smart Dual Thermal Network).

According to this procedure the potential of these thermal network typologies has been analysed for 2 different locations (Madrid and Bilbao), in order to include the impact of climatic conditions in the performed analysis. Figure 6 displays the EnergyPlus model of one of the buildings of the district. The usage patterns, included in this models have been adjusted to reproduce the specificities of the existing activities and the impact of user behavior on the energy requested by the buildings (occupancy patterns, internal gains, ventilation rates, thermal/visual comfort profiles, internal air quality and DHW demand profiles). Additionally, the geometry of the buildings provides high availability of roof or façade surface for solar collector deployment, with moderate shading and the possibility to deploy solar collectors with acceptable values of tilt and orientation.

On the other hand, thermal envelope quality (insulation, thermal mass, and airtightness) has been adjusted according to the considered climatic boundary conditions and current good practice standards, in order to have realistic values for the demands of the buildings. Table 5 displays the specifications of the Heating, Ventilation and Air Conditioning (HVAC) and distributed generation systems deployed at building level.

Figure 7 displays, the scheme of the TRNSYS model including the district plant, the distribution network and the connected buildings. The considered modelling detail enables the evaluation of all the existing district levels dynamics (heat generator performance, physical location of the buildings inside the district, distribution losses, pumping consumption, thermal substation efficiency and Virtual District Plant management).

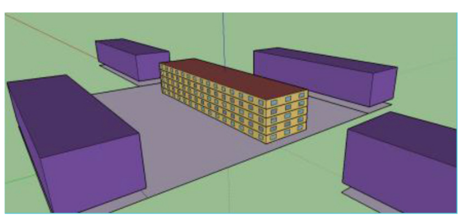

Figure 6: Geometry of the office buildings of the district.

Table 5: HVAC and distributed generation systems deployed at building level.

Reference scenario	
Heat supply	Connection to the thermal network
Cooling	Local through conventional compression chillers
Building connection	Unidirectional
HVAC system typology	Centralized system with 4 pipe distribution
Terminal units	4 pipe fancoils
Ventilation	AHU-s with preheating/precooling hydronic coils, heat recovery, demand controlled ventilation and free cooling
Settings	Heating system supply/return temperature: 60/50°C Cool water supply/return temperature: 7/12°C DHW production and storage temperature: 60°C
Innovative scenarios	
Heat supply	Connection to the thermal network, solar collectors and Virtual District Plant (Capstone C30)
Cooling	Conventional single effect absorption chillers (Heat supply from the thermal network) and innovative cooling collectors
Building connection	Bidirectional
HVAC system typology	As reference scenario
Terminal units	As reference scenario
Ventilation	As reference scenario
Settings	Conventional absorption chiller source temperature: 85°C Cooling collector heat source temperature: 90–95°C

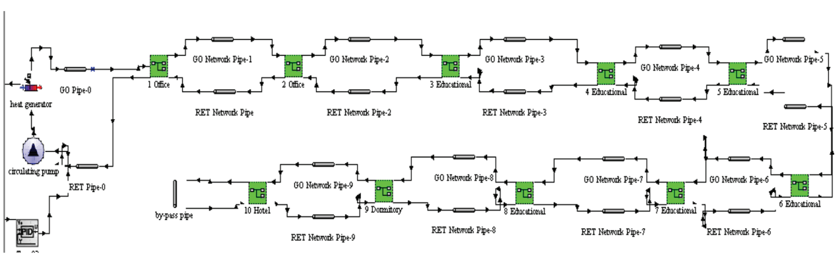

Figure 7: TRNSYS district heating system model.

5 RESULTS AND DISCUSSSION

Tables 6 and 7, summarize the main results obtained for Bilbao and for Madrid:

In the following lines, the results provided by the network potential evaluation process are summarized.

Table 6: Innovative thermal network potential assessment (Bilbao).

KPI-s	Reference Scenario	Smart TN	Smart Dual TN	Dual TN
Primary energy cons. (MWh)	3551.92	2987.30	3349.20	3577.70
Cooling electricity cons. (MWh)	275.2	255.5	34.25	34.25
Plant electricity cons. (MWh)	183.5	224.5	245.2	245.2
Electricity prod. (MWh)	1016.80	745.54	1143.40	1228.40
Operational cost savings (%)		11.87	12.40	6.96
Solar prod. increase (%)		62.77	200.67	134.45
Electricity prod. increase (%)		–26.67	12.45	20.81
Virtual Plant prod. increase (%)			84.44	

Table 7: Innovative thermal network potential assessment (Madrid).

KPI-s	Reference Scenario	Smart TN	Smart Dual TN	Dual TN
Primary energy cons. (MWh)	4412.02	3491.25	3731.00	4281.61
Cooling electricity cons. (MWh)	626.3	551.3	23.1	23.1
Plant electricity cons. (MWh)	135.4	162	169	169
Electricity prod. (MWh)	1033.09	705.92	1309.50	1461.90
Operational cost savings (%)		17.55	28.67	17.96
Solar prod. increase (%)		37.05	224.69	163.77
Electricity prod. increase (%)		–31.76	26.76	41.51
Virtual Plant prod. increase (%)			45.28	

– All the defined thermal network typologies produce significant operational cost savings, but the highest potential is displayed by the Smart Dual Thermal Network, with savings of up to 28.67% (Madrid). However, it is believed that the performed analysis underestimated the existing potential, due to a significant oversizing of the CHP capacity considered for the reference scenario.
– The Smart Network can provide an increase of the solar production of up to 62% (Bilbao).
– The Dual Network can provide an increase of 163.77% of the solar production and an increase of the total electricity production of up to 41.51% (Madrid).
– The Smart Dual Thermal Network can provide an increase of the solar production of up to 224.6%, an increase of the electricity production of the Virtual Plant of up to 45.28%, and a total electricity production increase of up to 26.76% (Madrid).

According to the performed analysis the impact of the innovative functionalities of the thermal network are maximized in locations with high solar irradiation availability and the presence of high cooling demands in the buildings of the district. In any case, it is necessary to extent the performed assessment to further study the impact on the potential of the Smart Dual Thermal Network of climatic conditions, the evolution of absorption technologies, feed in tariffs and energy prices.

6 CONCLUSIONS

Upgrading traditional district heating systems to optimized heating and cooling networks, operated as integrated systems, with optimized RES and CHP contribution must face huge technical and economic obstacles, such as the construction of a district cooling plant and the deployment of a dedicated cooling distribution network.

The innovative Smart Dual Thermal Network concept based on RES, CHP, and locally deployed sorption solutions, as generation technologies, has been developed in the frame of the FP7 A2PBEER project, to overcome these limitations, enabling the transition of buildings from consumers to prosumers. Additionally, in order to enable the configuration of the Virtual District Plant necessary for the implementation of the thermal network, and to facilitate the smart interaction between the buildings and the network, the Smart Dual Thermal Substation has been defined.

Finally, the first assessment of the potential of this innovative thermal network, through a specific co-simulation procedure based on EnergyPlus building models and a TRNSYS district heating system model, has been presented with promising results for 2 different climatic conditions.

ACKNOWLEDGEMENTS

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