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E-HUB

Energy-Hub for residential and commercial districts and transport

SEVENTH FRAMEWORK PROGRAMME

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Content

Executive Summary

Due to finite stocks of fossil fuels and the effect of greenhouse gas emissions, the amount of renewable energy from wind, biomass and solar energy etc. must strongly increase over present levels. However, due to the fluctuating nature of renewable energy supply, application of short term and long term **energy storage** and intelligent **energy management** systems are essential to match demand and supply of energy.

Thermal storage is sometimes called ‘the holy grail’ of energy neutral buildings. The consortium made good progress in improving several types of **thermal storage**, in particular on Thermo-Active foundations, Thermo-Chemical storage and distributed thermal storage.

The Multi Commodity Matcher (MCM) control algorithm developed in the E-hub project is able to match the supply and demand of electricity and heat simultaneously. The MCM control algorithm was demonstrated in three types of applications:

1. A simulation tool was developed in the project to carry out simulations of a virtual application of an advanced Energy Management System in five case studies: the districts of Amsterdam (NL), Freiburg (D), Bergamo (It), Leuven (B) and Dalian (China).
   The main conclusion is that the MCM was able to accommodate the introduction of technologies based on Renewable Energy Sources (RES) and/or Recovered Energy (REC) within the district (GREEN/Low Carbon scenario). It resulted in an important decrease in primary energy use and CO_2 emissions and leads to more beneficial cash-flows for the studied cases. Moreover, by introducing smart capabilities (in the “SMART” scenario) extra savings in costs can be realized. In the SMART scenario the environmental impact may decrease or increase depending on the business case selected.

2. The MCM was used to control the operation of several cogeneration units in a real lab environment, under conflicting demand profiles of heat and electricity.
   The main conclusion is that both in tests with and without thermal storage, the MCM shows robustness in control, coming close to the best thermo-economic solution. The latter was found in a simulation with the “ECoMP” optimisation software.

3. An ‘electricity only’ version of the MCM was applied in a full scale demonstration in the district of Tweewaters in Leuven, Belgium.
   The main conclusion is that the consortium set a best practice with the full scale demonstration of a high quality building equipped with a smart energy management system.

In the frame of a ‘Joint Exploitation Agreement, the simulation tool can be used by consortium members to continue to provide consulting services e.g. to municipalities in configuring energy neutral/energy efficient districts.

An important element is the acceptance of such an advanced energy system by stakeholders such as DSOs (Distribution System Operators), BRPs (Balancing Responsible Parties) and end users. Therefore, a number of new business models and service concepts, most of them based on the concept of ‘flexibility of demand’ were developed and applied in the case study simulations.

1 Introduction

Every day, we are extracting an enormous amount of oil, gas and coal from the earth. In that way, we are consuming solar energy that was captured over millions of years by plants and converted into ‘fossil fuels’.

The amount of fossil energy in our earth is huge but in the end it is limited. People are becoming increasingly aware that one day, fossil fuels will run out. Being an ‘energy-addicted’ society, we will have to find alternative sources, such as wind, the sun (Photo-Voltaic and solar thermal panels), biomass etc.

Mismatch between supply and demand of energy

The problem with renewable sources is that the energy they supply “is never there when you need it”. For instance, Photo-Voltaic panels deliver most of their electricity on sunny days around noon, while the highest demand for electricity (in dwellings) is in the evening when people turn on lights, television sets etc. A second example of a mismatch is the heat supplied by solar thermal panels in summertime and heat demand in wintertime, as illustrated in the graphs below.

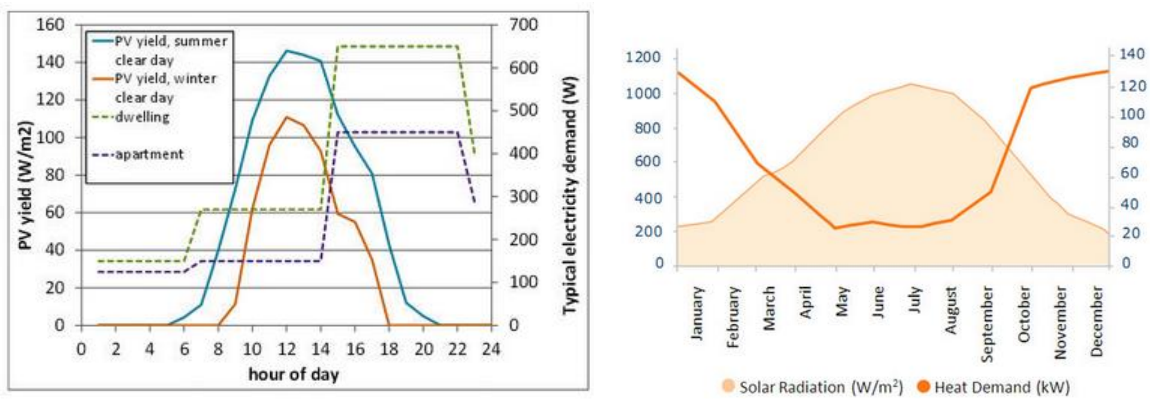


Figure 1: Mismatch between supply of renewable electricity from Photo Voltaic panels and electricity demand (left) and mismatch between supply of renewable heat from solar thermal panels and heat demand

How can we match energy supply and demand? We can do so by a combination of energy storage, bridging the time between supply and demand and by using a smart control of appliances in order to shift the time of demand.

Changes in the energy supply

Our society is changing in many ways. The number of electricity consuming appliances is growing fast, like smart phones, tablets and white good appliances. Numbers of large consumers like electric vehicles are growing faster and faster.

Figure 2: Tesla electric car

In the future, the demand from all these users may be so high at certain times that one cannot charge one's car because of limited capacity of the electricity grid. It will be the end of happy and unlimited energy consumption.

We expect that in the future, the harsh rules of capitalism - scarce commodities are more expensive - will apply to the energy supply. That means that energy will be more expensive in times of shortages of supply and cheaper in times of abundant supply. And so, future energy tariffs will vary from hour to hour rather than the flat tariff in use today.

When a home-owner wants to save on his energy bill, he can sit and wait next to his energy price indicator for the price to go down. Or he may use a smart control system to do it for him. The control system will know when the electric car needs to be charged (e.g. in the next day at 7 am) and it may use the weather-forecast, predicting when prices will be low due to abundant supply from off-shore wind farms. All this information will be used to ensure that the car is charged in the morning at the lowest possible price.

The Powermatcher © and MultiCommodity Matcher control software developed in this project are well prepared for these kind of changes. A smart citizen using smart controls will be prepared for the future.

2 Results

An overview of the main tasks in the E-hub project is given in Figure 3. The elements in the different boxes are discussed in the following chapters.

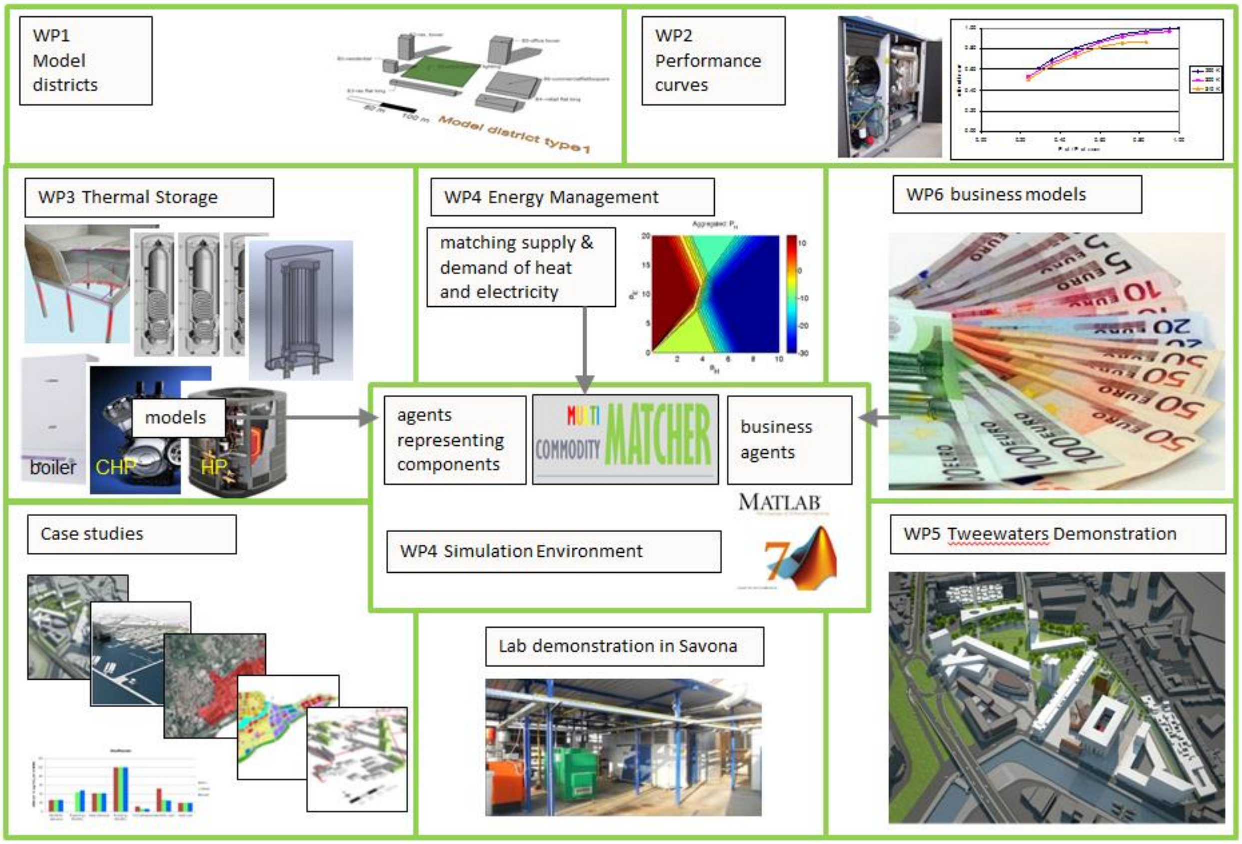
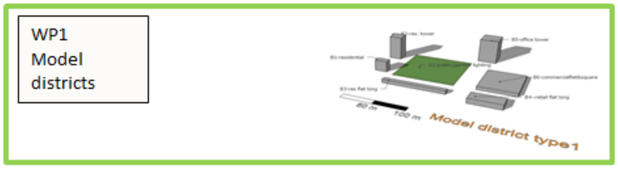


Figure 3: overview of the main tasks in the E-hub project.

2.1 Work package 1 System Definition



Work packages 1 and 2 can be characterized as preparatory for work in later work packages. In work package 1, we identified six Model District Types that can represent typical residential and non-residential districts across Europe. The model districts are intended to prepare for the evaluation of the case studies in WP6. Monthly energy demand for heating, cooling and electricity was calculated. The districts are shown in Table 1 below.

Table 1: Overview of Model District Types

Model district	Description	climate zone	District could be located in:
type 1	**Urban or suburban, mixed use** (i.e. residential, commercial and services), medium density mid-rise buildings from 1946 to present	(Central Europe)	Amsterdam (NL) Munich (GE) Freiburg (GE)
type 2A	**Residential district**, suburban or exurban area, buildings aged from 1971 to present, medium/low density, mid-rise buildings	(Southern Europe)	Athens (GR) Bergamo (IT) Malaga (SP)
type 2B	**Residential district, as 2A**	(Northern Europe)	Helsinki (FI)
type 2C	**Residential district, as 2A**	(Central Europe)	Amsterdam (NL) Munich (GE) Leuven (B) Freiburg (GE)
type 3	**Business district/office park** in a metropolitan or urban area with medium density high-rise and mid-rise buildings aged from 1981 to present	(Central Europe)	Amsterdam (NL) Munich (GE) Freiburg (GE)
type 4	**Multifunctional development centre** with mixed use (i.e. residential, commercial and services), with medium density mid-rise buildings aged from 1981 to present	(Central Europe)	Amsterdam (NL) Munich (GE) Freiburg (GE)

In addition, a survey across eight European countries was made to study ownership and management of buildings and electricity grids and heating networks to be used in the business models in WP6.

Table 2: Details of power generation, power distribution, 'Last mile' distribution and Sale in European countries of case studies (WP6)

				€
COUNTRY	**Power generation**	**Power distribution**	**'Last mile' distribution**	**Sale**
Italy	2 398 companies e.g. ENEL, EDISON, ENI, A2A, IREN	TERNA SpA.. Other minor operators: e.g.Self Rete Ferroviaria Italiana, TELAT, Agsm Trasmissione (Verona)	1 concession per municipality 143 companies, owned by public authorities (44%), natural persons (33%), other companies (21%).	143 companies
The Netherlands	Large producers of electricity: NUON, Essent, Electrabel, Intergen, Delta, E.ON	TenneT (manager of the national grid)	Cogas Infra & Beheer B.V, Delta netwerkbedrijf, Enexis, Liander, NRE network, Rendo, Stedin, Westland Infra	29 energy supply companies (2011) like Greenchoice (renewables only), Essent, NUON, OXXIO
Belgium	Electrabel, Essent, Nuon, RWE, Aspiravi, Ecopower, Wase Wind and Beauvent.	From 2002, Elia is transmission grid administrator with a monopoly on electricity >70kV.	In Flanders, Elia is distribution administrator for the transmission nets of 30 -70 kV. Local grids below 30kV administered by local companies SIBELGA, EANDIS, INFRAX, ORES (no free choice for the consumers)	Standard suppliers: Electrabel, Luminus other:Anode, Ecopower, EDF B, Endesa Energia, Eneco, EON, Lampiris, Nuon, SPE, Thenergo
Germany	Mainly E.on, RWE, Vattenfal, EnBW (80% share). Additionally, many small local utilities.	Mainly Tennet TSO GmbH, 50 Hertz Transmission GmbH, Ampiron GmbH and EnBW Transportnetze AG.	About 950 small local utilities.	Distribution companies.

Finally, an evaluation methodology was made, yielding kpi's on energy, ecology and economy, to be used in the evaluation of the case studies in WP6

2.2 Work package 2 Energy Conversion & Storage

In work package 2, we produced an inventory of existing technologies, to be used in the simulations in WP4. When using smart control of power and heat generating systems, they are expected to be operated differently from stationary systems running at nominal conditions, as is currently the case e.g. in large electricity plants. Therefore, intermittent operation, start-up behaviour and operation at partial load are important aspects to consider.

Therefore, representative real equipment such as a micro turbine CHP, an absorption cooler unit, an internal Combustion Engine (with a 1.2 litre Fiat engine), a fuel cell gas turbine hybrid system and a Stirling Engine were tested in the lab of TPG-DIME. Their performance was evaluated under different operating conditions. Figure 4 shows the electrical efficiency of the micro gas turbine CHP at partial load for different ambient temperatures and Figure 5 shows the electrical efficiency of the internal combustion engine CHP. In spite of the difference in technology, the curves show a remarkable resemblance.

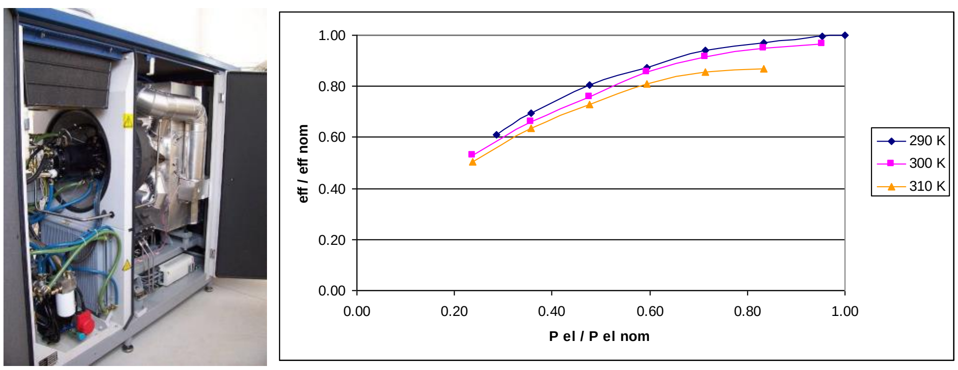


Figure 4: Picture and electrical efficiency of the micro gas turbine CHP at partial load for different ambient temperatures

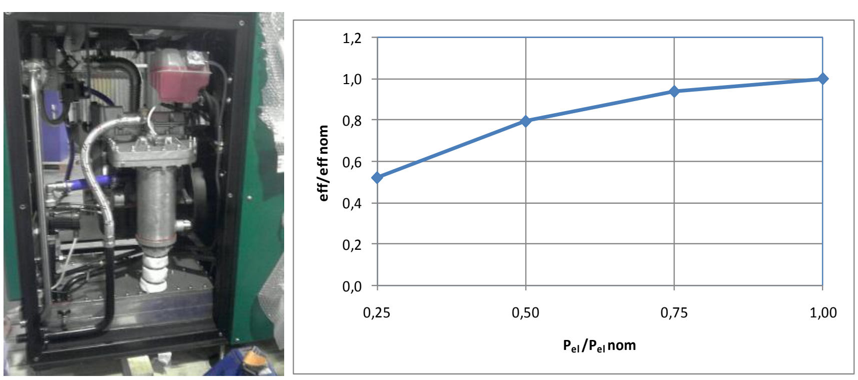


Figure 5: Picture and electrical efficiency an internal combustion engine CHP at partial load.

The characteristics of the equipment were implemented in the numerical models used to run the simulations in WP4.

WP2 also proposed, for each of the model districts, heat and electricity generating equipment, based on the energy profiles of the district and the analysis of a number of real cases with renewable energy and energy efficient equipment. These systems, based on experts' assessments, are called the 'best practice' systems.

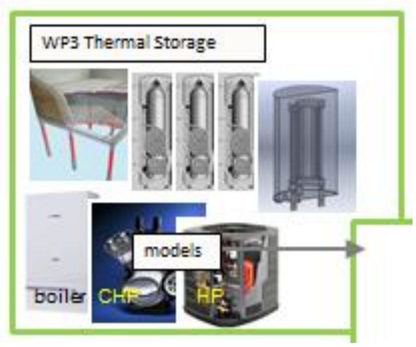
Following the methodology developed in WP1, the kpi's (key performance indicators) of energy, ecology and economy were calculated for a number of alternative systems. This resulted in an '*optimised'* system, with a share of renewables of at least 20% of the total energy demand. The table below shows the characteristics of a 'Business as Usual' or 'reference' system, the 'best practice' system and the 'optimised' system.

Model district	Description	Reference system	Best Practice including renewables	OPTIMUM SYSTEM FROM KPI'S
type 1	Urban or suburban, mixed use, Munich	Individual (R[1]) and central condensing boilers (NR), electrically heated storage systems (NR) and compression chillers (NR).	Central biomass fired boilers, compression chillers (NR) + Photovoltaics	District heating + 593 kWp PV
type 2A	Residential, Athens	Individual (R) and central condensing boilers (NR), electrically heated storage systems (NR), individual split heat pumps for cooling (R) and compression chillers (NR).	Central gas fired condensing boilers, solar thermal panels for DHW (R), individual split heat pumps for cooling (R), compression chillers (NR) + Photovoltaics	Best practice + 129 kWp PV
type 2B	Residential, Helsinki	Individual (R) and central condensing boilers (NR), electrically heated storage systems (NR) and compression chillers (NR).	Central biomass fired boilers, compression chillers (NR) + Urban Wind Turbines	District heating + 255 kWp PV
type 2C	Residential, Munich	Individual (R) and central condensing boilers (NR), electrically heated storage systems (NR) and compression chillers (NR).	Central biomass fired boilers, compression chillers (NR) + Photovoltaics	District heating + 200 kWp PV
type 3	Business district/office park, Amsterdam	Central condensing boilers, electrically heated storage systems and compression chillers.	ATES (Aquifer Thermal Energy Storage)+ Large wind turbine(s)	Best practice + 1898 m^2 Large wind turbines (swept surface)
type 4	Multifunctional development centre, Amsterdam	Individual (R) and central condensing boilers (NR), electrically heated storage systems (NR) and compression chillers (NR).	Combi-heat pumps (R), ATES (NR) + Urban Wind Turbines	TAF + 1294 m^2 Urban wind turbines (swept surface)

Table 3: 'Business as Usual' or 'reference' system, the 'best practice' system and the 'optimised' system for the model districts.

[1] (R) = residential buildings, (NR) = non-residential buildings

2.3 Work package 3 Components and Techniques Development



In WP3 we continued development of a number of thermal storage components and produced a number of numerical models of thermal/electricity storage components and of heat /electricity generation equipment for use in the simulation environment in WP4.

2.3.1 Thermo-Active Foundations

The work on Thermo-Active Foundations (TAF) aimed to improve the heat transfer between soil and piping network by using alternative materials Simulations were carried out using calibrated high detail 3D-FEM models (Figure 6). Parameters studied include piping and concrete heat transfer, piping layout

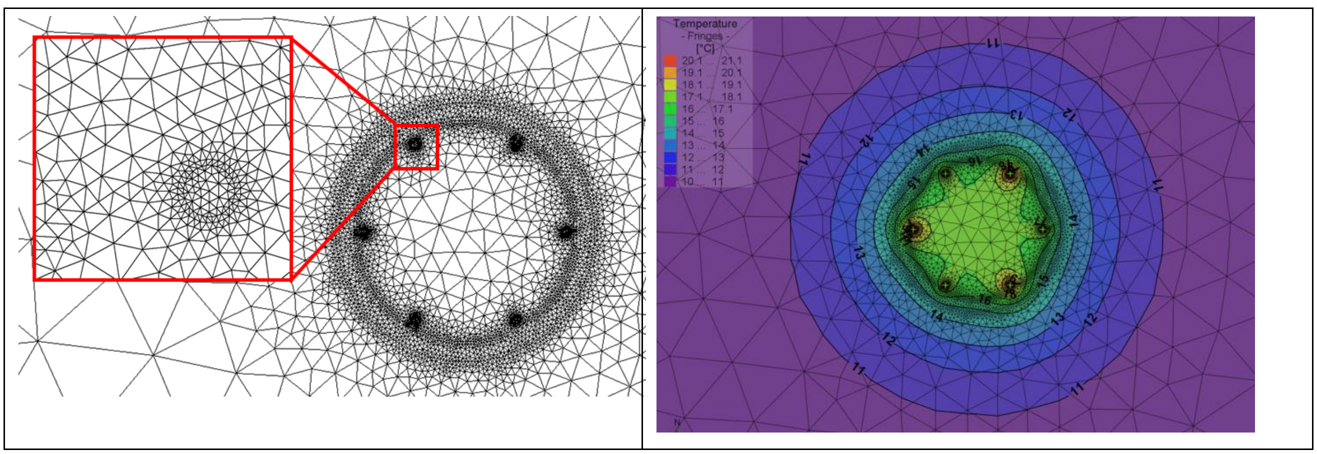


Figure 6: Calibrated high detail 3D-FEM models to analyse the performance of new materials in thermo-active foundations.

The use of thermally enhanced piping material appears to have little effect on the thermal performance of the energy pile. However, thermally enhanced concrete (15% more expensive) increases the performance in base load operation by 10-25 % and in peak load operation by 25-30%

In the work on thermo-active foundations, partners SOL and HSW developed a simple implicit model to be used in the Matlab simulation environment developed in WP4, allowing the assessment of TAFs in a district energy system.

The simplified model was compared against analytical solutions and CFD (Computational Fluid Dynamics) data and it has also been compared with calibrated models made with EED commercial software, as shown in Figure 7

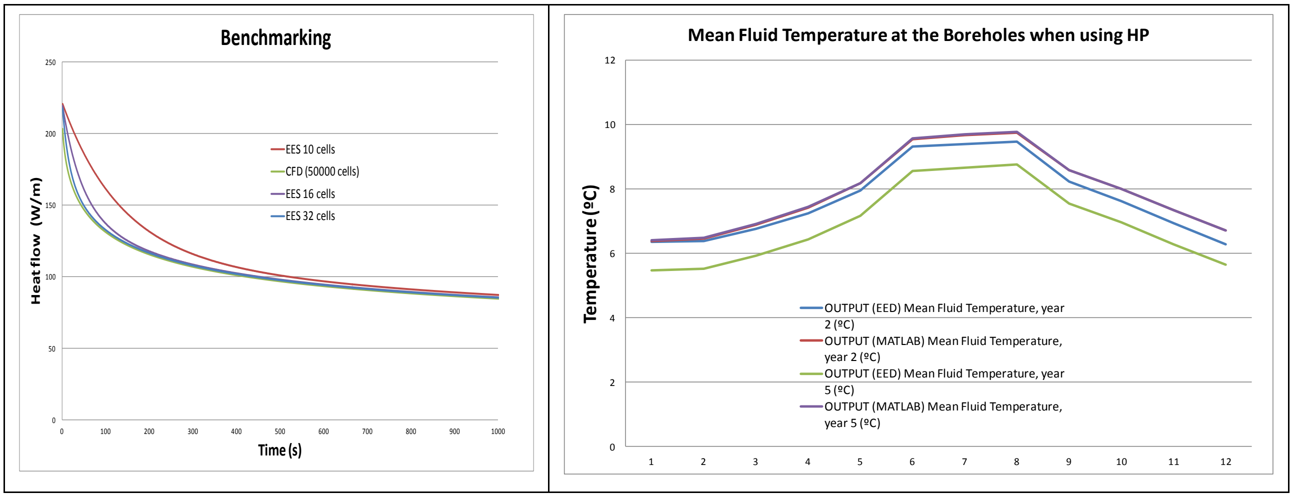


Figure 7: (left) Comparison between a simple implicit model (EES10) and analytical solutions and CFD data, (right) Comparison between the simplified model implemented in Matlab and the specific software EED (Earth Energy Designer)

The integration of the TAF system at building level was also studied. The goal was an optimal low-temperature piping network, with a single central heat pump or decentralised heat pumps.

Model district 4, located in Western Europe, was chosen to virtually build a low temperature district heating network. It contains five buildings with a ground area of 6,500 m² in a total area of 16,500 m². For this district, the two most efficient and practically proven possible ways of balancing thermal energy on a district level were analysed, shown in Figure 8.

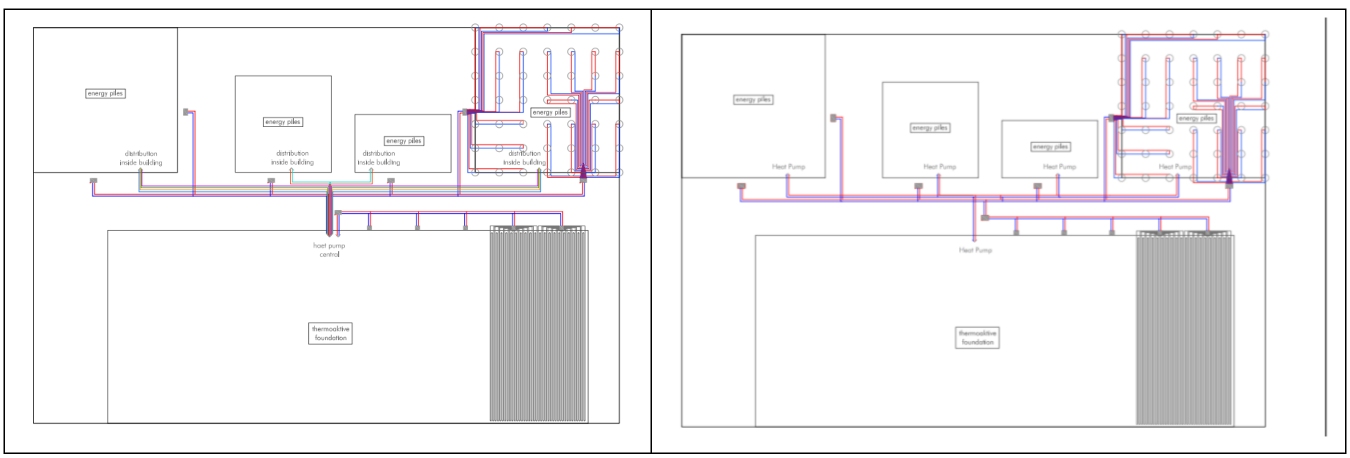


Figure 8: (left) first variant that uses a single heat pump room inside a centrally located building, from which high temperature thermal energy is distributed, (right) second variant that consists of two separate (but connected) networks over which low temperature is distributed for use by heat pumps inside the buildings.

2.3.2 Thermal Road Solar Collector system

The Thermal Road Solar Collector (TRSC) developed in this task is to be used in combination with Thermo-Active Foundations to restore the heat balance of the soil over a summer and winter period. The work on the optimisations of the TRSC (structurally and thermally) aims to improve the heat transfer between pavement and piping network to maximise TRSC outlet temperature. The higher the temperature level, the higher the efficiency of the total energy system.

Simulations were made to determine efficiency curves for the road solar collector. Parameters studied include pipe diameter, depth and spacing, insulation layer under pipe array, asphalt IR reflectivity. As an illustration, Figure 9 shows the heat collection rate of a road solar collector as a function of pipe depth and pipe spacing

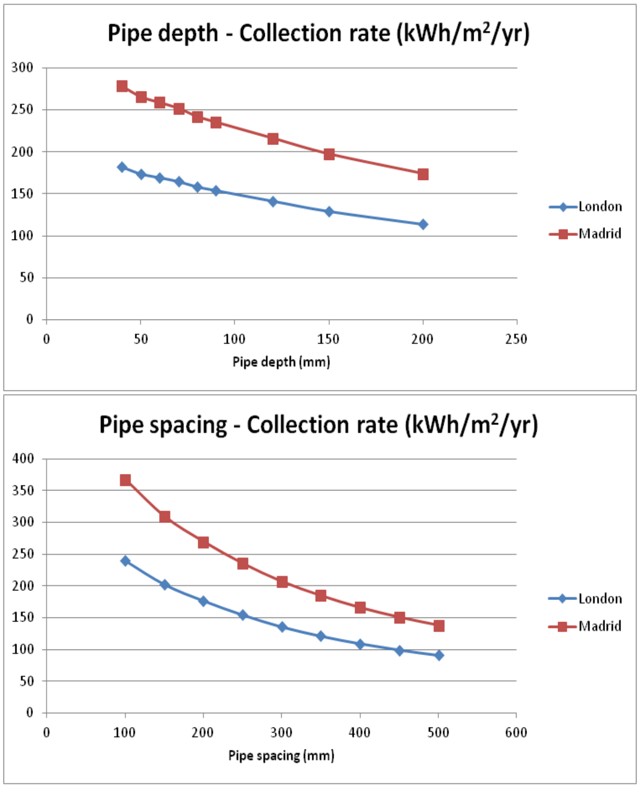


Figure 9: Annual heat collection curves of road solar collector as a function of pipe depth (left) and pipe spacing (right) in the climates of London and Madrid.

In addition to the simulations, structural tests were carried out to investigate the strains and wear of TRSC lay-outs.

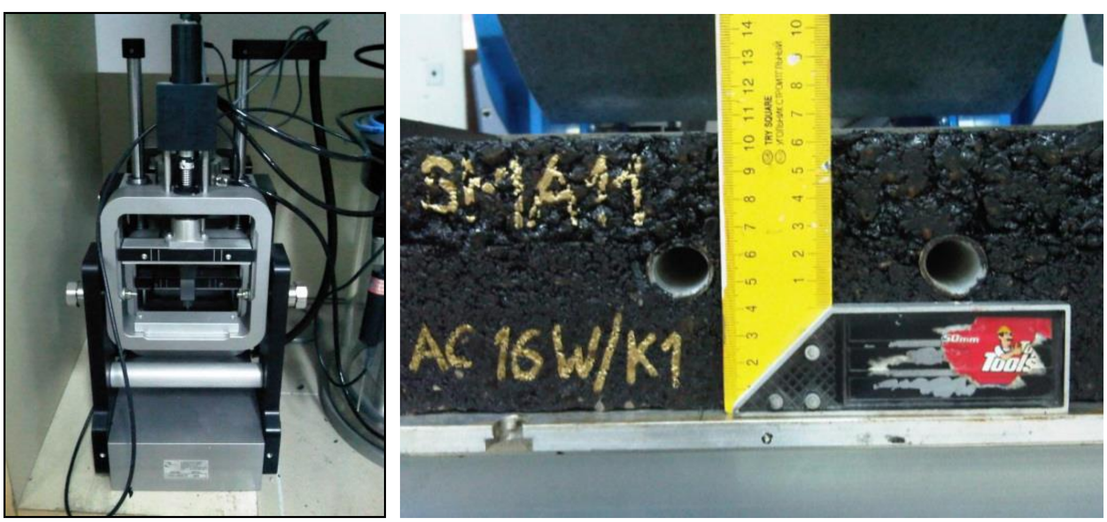


Figure 10: Structural tests of pipes in asphalt carried out at Mostostal.

Tests verified that the addition of a thin layer of resin in the top few mm of the asphalt allows the location of the pipe system at the bottom of the wearing course.

As a result, a validated model is available to calculate optimal piping layout, depending on weather and traffic conditions. In addition, a simple thermal model of the solar thermal road collector was made in Matlab, for use in the simulation tool in WP4. TRNSYS simulations were used to validate the simplified model (Figure 11).

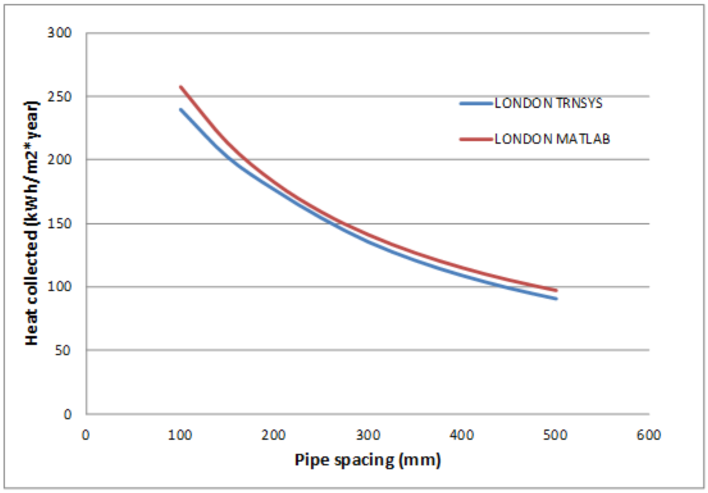


Figure 11: Annual heat collected by a typical layout of road solar collector, as function of pipe spacing, for the climates London. Comparison between results of simple Matlab model and TRNSYS

2.3.3 Thermo Chemical Storage

ECN and TNO investigated long term thermal storage using Thermo Chemical Materials (TCM's). The aim was to construct and test Thermo-Chemical Storage reactors, supported by a validated theoretical model.

ECN decided to concentrate on atmospheric TCM systems (using moist air) while TNO pursued the route of sub- atmospheric TCM systems (using water vapour without air). The first has the advantage of being more suited for practical purposes, but has the disadvantage of having to provide a forced airflow through the system, requiring auxiliary electrical energy. The second has the advantages of higher power density and fast charging and discharging of the store, while its main disadvantage is a higher complexity as a near-vacuum has to be maintained.

At **ECN,** a 15kWh heat storage system was designed, built and initial test were carried out. The system is based on an open sorption concept to achieve a simple and low cost solution for the storage containers. It contains 2 vessels of 112 dm^3, each filled with 75 kg of zeolite 13X grains. The storage capacity reached 14 kWh and thermal powers for charging and discharging are in the range of 0.5-1 kW. The system is shown in Figure 12 below.

Figure 12: Pictures of the open sorption storage system. Left, the storage vessels, and middle the air handling unit both under construction. Right, the sorption system in its final state in the laboratory.

The temperature inside the zeolite reactor was measured at various heights. Figure 13 shows the graphs of the zeolite bed temperature over time. The temperature in the bed rises from bottom to top, following the air supply direction. The temperature gradient in the bed points to a moving reaction zone of desorption. In discharging mode, cool and humidified air is blown through the dried zeolite and the water vapour is adsorbed. The heat of sorption is released and over time, the zeolite and the air increase in temperature to values of up to 70°C. After 25 hours of discharge the zeolite has reached its equilibrium sorption capacity and heat release stops rather rapidly. The steep drop in temperature through the bed again indicates a distinct reaction zone inside the bed that gradually shifts from bottom to top.

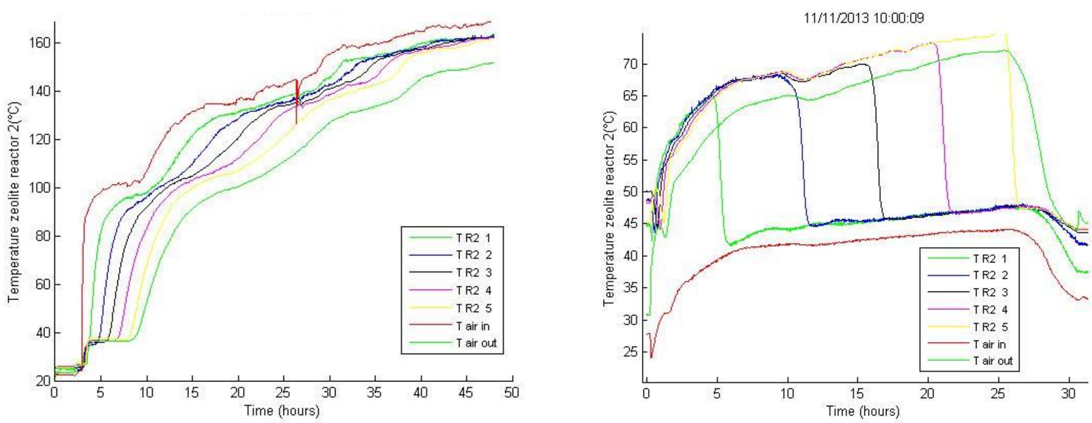


Figure 13: Measured temperature profiles in the zeolite reactor (TR1-TR5) and temperature of the air inlet and outlet during charging (left) and discharging (right) of the system.

In addition to the experimental work, a dynamic simulation model of an open sorption reactor was validated, which will be a valuable tool for future upscaling.

In conclusion, the open sorption concept allows simple storage reactor design, but further improvements are needed, including: 1) reduction of auxiliary electricity, 2) reduction of thermal losses in air handling, 3) application of materials with higher energy density.

At **TNO**, a 3 kWh-reactor filled with 40 kg of zeolite 5A spheres was built and tested. It contains eight heat exchangers connected in parallel. The left of Figure 14 shows a heat exchanger, the right shows the reactor vessel containing eight heat exchangers.

Figure 14: Heat exchanger (left) and reactor vessel containing eight heat exchangers (right).

Experiments showed stable sorption material behaviour with temperature lifts of 20 – 50°C, matching levels in building heating demands. The energy content appeared to depend on operating conditions, in particular those during the drying (desorption) process, as shown in the left in Figure 15. The energy content measured was lower than that derived from Clausius-Clapeyron curves found in the literature. Most likely, the zeolite used differed in material characteristics from the zeolite on which the curves were based.

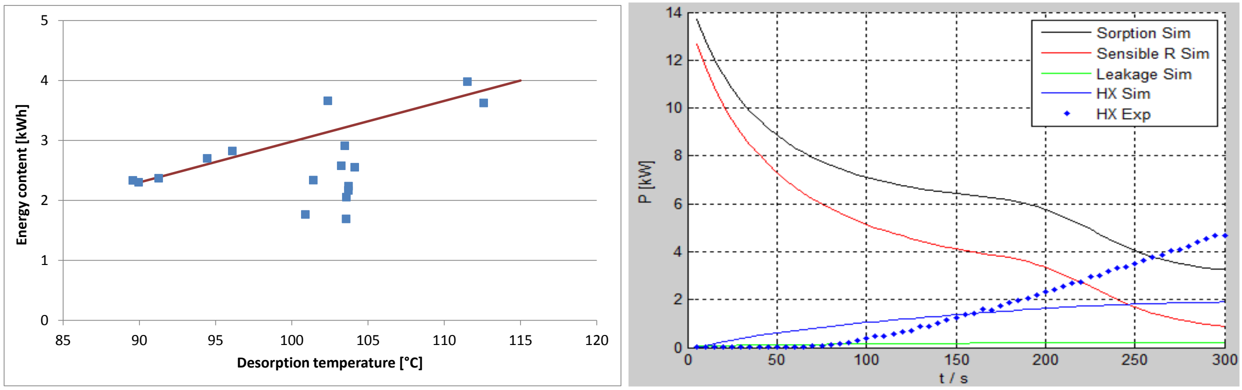


Figure 15: Energy content of the TNO 3 kWh reactor vs. desorption temperature (left) and model calculation (lines) and experimental values of thermal powers as a function of time (right) for a particular experiment.

In addition to the experimental work, a numerical model was developed that describes the physical processes of evaporation, absorption, heat transfer etc. taking place in the evaporator unit and reactor vessel. Model calculations based on first guesses of parameters yielded a reasonable fit with experimental results, as shown in the right graph of Figure 15

Finally, the expertise and experience gained was used to design a 15 kWh reactor, based on the 3 kWh module. The height of the vessel was maximised to 2m in order to allow installation in a dwelling. With 175 kg of zeolite at the current performance yields a value of 16 kWh for the energy content. Because of the higher packing density, the system energy density (based on the volume of the vessel rather than the volume of the zeolite) increased from 0.08 GJ/m^3 for the 3kWh module to 0.13 GJ/m^3 for the 16 kWh module. The 3 kWh module and the 16 kWh module are shown to scale in Figure 16.

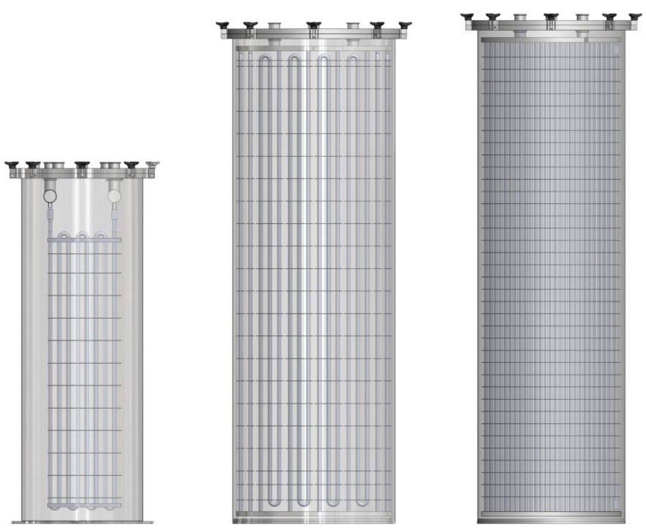


Figure 16: The 3 kWh module (left), the 16 kWh module with rectangular heat exchangers (middle) and cylindrical heat exchangers (right), all shown on the same scale.

2.3.4 Distributed thermal storage

VITO investigated the benefits of distributed thermal storage. Instead of a large centralised heat storage vessel, smaller individual vessels can be located in households or offices, with the advantage that the heat is stored close to where it is needed. Excess production of thermal energy (from solar collectors or from a CHP) need not be discarded but can be stored for future use.

VITO designed an experimental setup with 4 vessels including the emulation of heat production and consumption. Two vessels, shown in the bottom left of Figure 17 are suited for domestic hot water storage only, while the two vessels in the top left are suited for both domestic hot water storage and space heating.

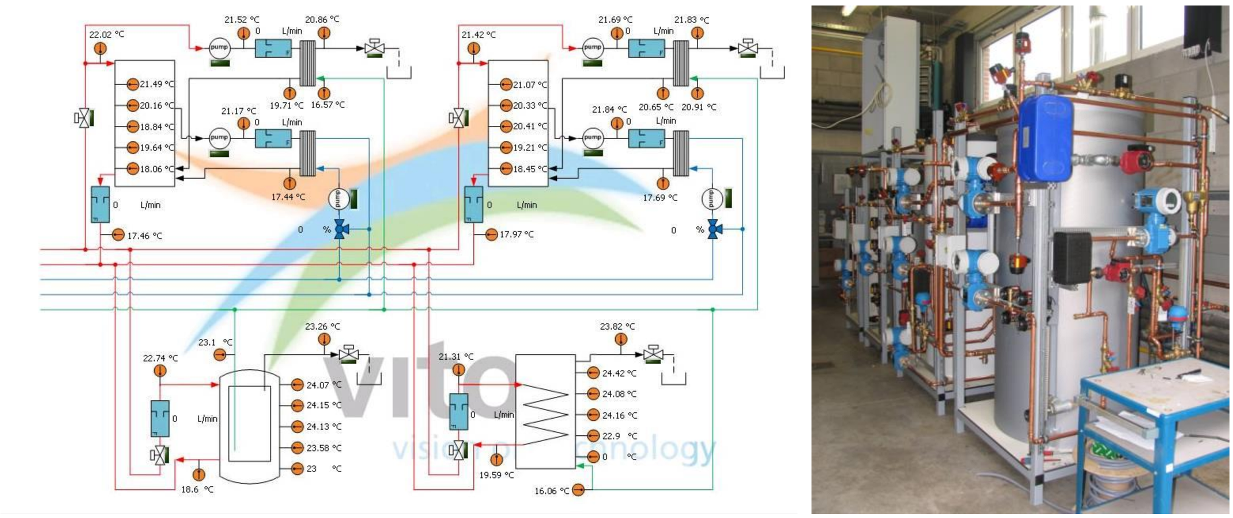


Figure 17: Schematic of the experimental setup with instrumentation and picture of the test rig in the lab.

Different heat storage strategies for the vessels in a district heating grid fed by a CHP are compared for energetic and economic performance, using a 'hardware-in-the-loop' simulation model. The flexibility resulting from the storage vessels is used to actively control the CHP, which in this way can produce electricity at times of high electricity prices. The results of the simulations show that the control framework developed performs well, resulting in higher profits in operating the CHP. The profit resulting from the different storage strategies are shown in Figure 18.

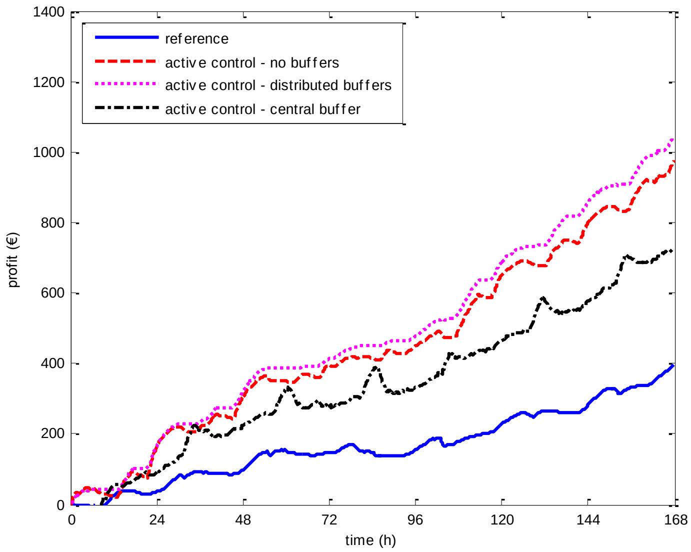


Figure 18: Cumulative operational profit for the different storage strategies during a one week test.

The configuration with distributed heat storages (pink dotted line in Figure 18) performs best, however only slightly better than the active configuration without buffers (red dashed line). The results for the central buffer case (black dotted line) are a little worse, but still a lot better than in the reference case (blue line) without active control. The reasons for the lower performance is that the thermal mass of the buildings, which is activated in the first two configurations, is rather high compared to that of the buffers, resulting in much more flexibility and consequently higher profits. Summarizing, the results show that active control of the CHP is able to increase the profit of the CHP significantly.

VITO also studied a method to reliably determine the State of Charge (SoC) of a water based storage vessel with a minimum number of temperature sensors. A model was developed taking into account heat losses and heat exchange between water layers, heat convection when the system is drained, mixing and heating. The model was able to estimate the temperature profile in the buffers with a small number of sensors typically 4). It was also found that the positions of the sensors are crucial parameters to obtain good results.

2.3.5 Modelling of components

When doing simulations of energy management systems on district level, we need numerical models of thermal/electricity storage components and of heat /electricity generation equipment as well as a dynamic numerical model of the building is a district. As the simulation environment in WP4 was going to be programmed in Matlab, the components models would also have to be modelled in Matlab.

The starting point for the components was the list of equipment proposed in WP2 for the model districts. The final list is shown in Table 4 below. For each model, a numerical model was written in Matlab code and validated by comparing the output to either measurements of real equipment, or results of commercial software (e.g. TRNSYS) or checked for correct operation.

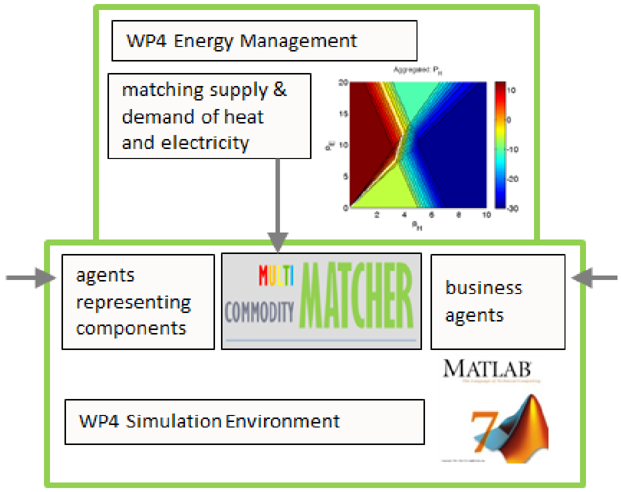
Table 4: List of components modelled for the simulation of E-hub system in WP4.

Model category	**Model name**	**Partner**
Producer, thermal	Boiler	TPG-DIME
	Heat Pump (air to water)	Fraunhofer
	Geothermal Heat Pump	SOLINTEL
Producer, electrical & thermal	CHP Microturbine	TPG-DIME
	CHP Stirling	TPG-DIME
	CHP Internal Combustion Engine	TPG-DIME
	CHP Fuel cell hybrid system	TPG-DIME
Producer, cold	Absorption chiller	DAPP
	Compressor chiller	DAPP
Storage, thermal	Daily Water Storage	VTT
	Thermochemical Storage	TNO, ECN
	Thermo active foundation	SOLINTEL, HSW
Storage, electrical	Electrical Storage	TPG-DIME
Renewable energy, thermal	Thermal Solar Collector	VTT
	Thermal Solar Road Collector	SOLINTEL, ICAX
Renewable energy, electrical	Renewable energy generators (wind, photovoltaic)	TPG-DIME

In particular in residential districts, the buildings are the main consumers of thermal energy. To model the buildings in a district, a simple dynamic model was made that allows the aggregation of a large number of individual buildings of similar thermal performance. This way, the district can be represented by a limited (typically 5-15) number of aggregated buildings, allowing the definition of their space heating and space cooling demands during a simulation run. As long as the indoor temperature in the buildings remains between certain boundaries, the space heating demand and space cooling demand of each building has some degree of flexibility.

In addition the libraries of the ECoMP and TRANSEO software, which constitute proprietary knowledge of partner TPG-DIME, were enriched with a number of models of new components.

2.4 Work Package 4 Energy Management



Simulation environment

This work package is the pivotal work package, where a simulation environment was developed. In an early stage of the project it was decided to program the simulation environment in Matlab as this programming language offered the required functionality and flexibility. In addition, Matlab expertise was available at all partners contributing to the development of the simulation environment. The latter includes:

- The implementation of the models of energy generation and storage equipment produced in WP3, represented by model agents. The agent of a component produces a bid functions which is the translation of the state of the component (e.g. for storage components: the State of Charge) into a willingness to consume or supply energy.

- The simplified model of aggregated buildings to calculate the space heating demand of the district.

- A heating network and electricity grid connecting energy producers and consumers. A Graphical User Interface (GUI) was made to facilitate the configuration of the district.

- Off-line calculation of electricity and Domestic Hot Water (DHW) demand profiles of the district. The electricity profile is in the form of a so-called ‘flex-graph’, giving the boundaries between which momentary electricity demand can vary as a result of time-shiftable appliances in the district such as white good appliances.

- Business agents representing Business models based on flexibility of demand:
  1. time of use/ToU business agent and
  2. peak shaving agent, which can also be considered as a ‘reduce imbalance cost’ business agent as they are based on similar principles.

- The MCM (Multi Commodity Matcher) control algorithm, discussed below. However, the simulation environment is open to work with alternative control algorithms if they comply with the interfaces described.

After the simulation, the performance of the energy management system can be assessed by analysing a number of predefined Key Performance Indicators (KPI’s) on energy use (kWh) economy (euros), ecology (CO2 emissions) and KPI’s related to peak shaving.

Control algorithm

In the project, an energy control algorithm called the Multi Commodity Matcher (MCM) was developed to match supply and demand of electricity and heat simultaneously on district level.

Several technologies are available for matching the supply and demand of energy. In this project we used agent based technology, used e.g. in the Powermatcher ® or IntelliGator ® software. In fact, the MCM developed in this project is an extension of the Powermatcher concept (which is for electrical power only) to electricity and heat, inheriting the Powermatcher's advantages of scalability and user autonomy.

Instead of a one-dimensional bid curve for a single commodity (electricity) we need to define two 2-dimensional bid surfaces, one for electricity and one for heat. For each multi-commodity agent, the bid surfaces represent the willingness to consume or produce electricity and heat at a range of electricity and heat prices. As an illustration, the figures below show the bid surfaces of a heat pump.

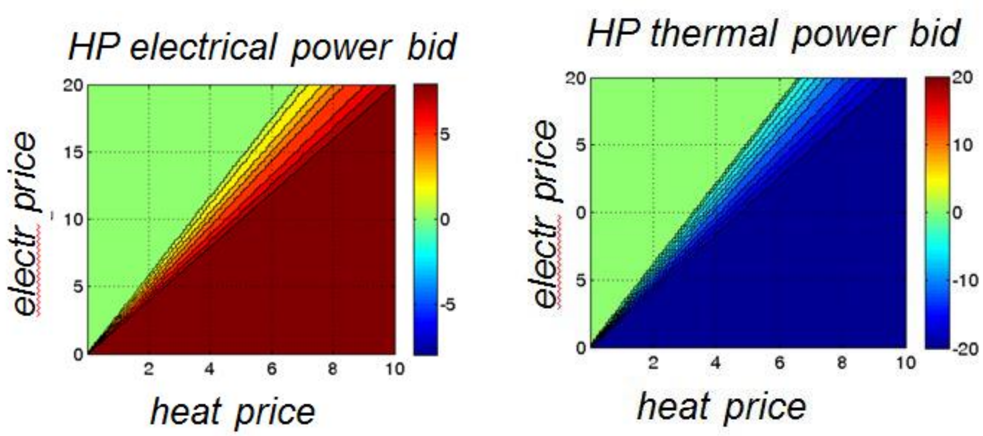


Figure 19: Electrical power bid surface (left) and thermal power bid surface (right) of a heat pump. The colours represent the amount of power the heat pump is willing to produce as a function of the prices of heat and electricity. As an example, at an electricity price of 5 €ct/kWh and a heat price of 6 €ct/kWh the heat pump will be fully on, consuming 6.7 kWh of electricity and producing 20 kWh of heat

The bid surfaces for each commodity can be aggregated over all devices in the market cluster. The result is shown in the graphs below.

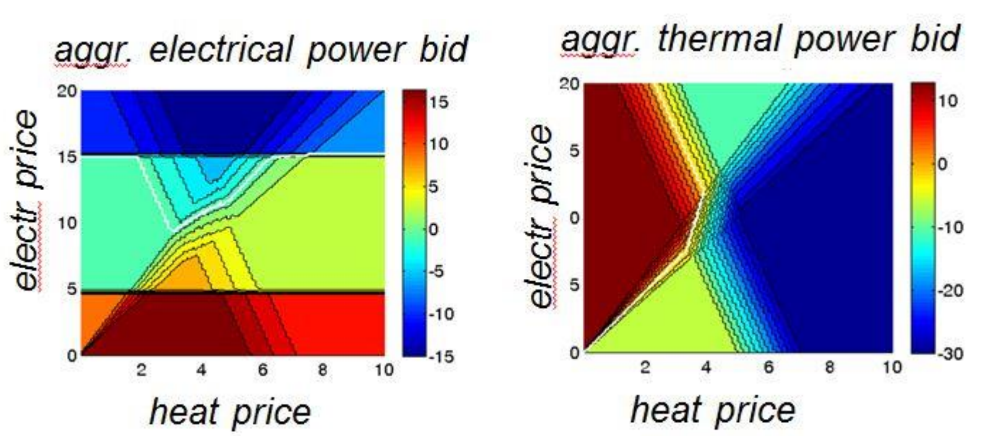


Figure 20: Aggregated bid surfaces for electricity (left) and heat (right). Equilibrium lines shown in white.

In each figure two equilibrium lines stand out in white where production and consumption are balanced. The equilibrium point, at which both electrical power and thermal power supply and demand are in balance, is found at the intersection of both ‘white’ lines.

TNO as holder of the IP to the MCM decided not to apply for a patent but instead intends to make this the standard in the field of agent based control systems. To this end, TNO is involved in the formation of an alliance called the Flexible Power Alliance Network, see http://www.flexiblepower.org/nl/

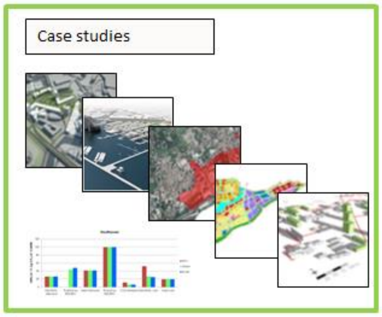
The MCM control algorithm was used in three types of applications which are discussed in the next chapters:

1. Simulations of a virtual application of an advanced Energy Management System in five case studies

2. Controlling the operation of several cogeneration units in a real lab environment, under conflicting demand profiles of heat and electricity

3. Full scale demonstration in the district of Tweewaters in Leuven, Belgium

2.5 Application of smart energy management in Case Studies



The simulation environment was used to simulate a virtual application of a smart energy management system in a number of case studies. The main characteristics of the districts are summarized in Figure 21 below.

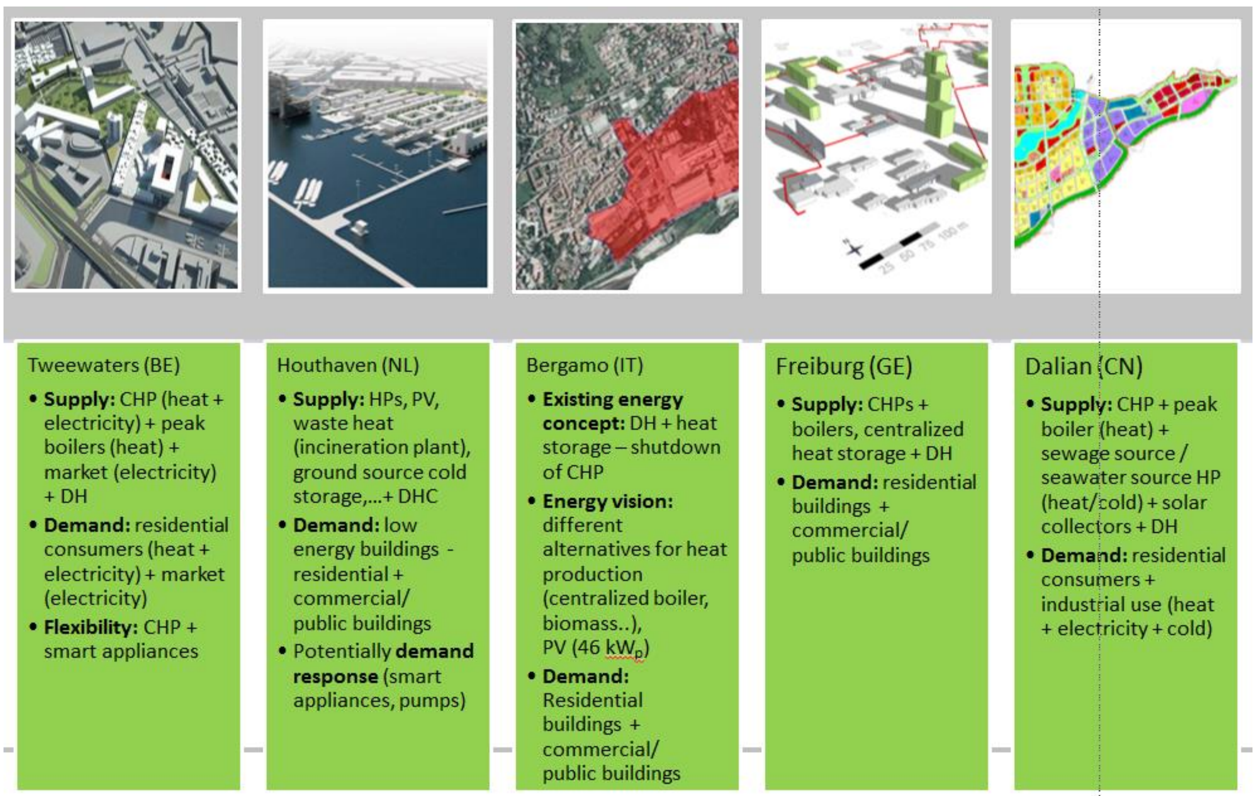


Figure 21: overview of the districts with detail on their energy system

The simulations of the case studies were carried out according to three scenarios:

1. A BAU (Business As Usual) scenario, using a conventional energy supply system.
2. A Green or Low carbon scenario, implementing RES (Renewable Energy Sources) and REC (Recovered energy) technologies.
3. A Smart scenario, similar to scenario 2 but run with a smart energy management system, making use of the flexibility in demand.

Annual profiles with hourly time steps were produced. As an illustration, Figure 22 shows the annual electricity profile and heat profile during the whole year in the BAU scenario of Tweewaters.

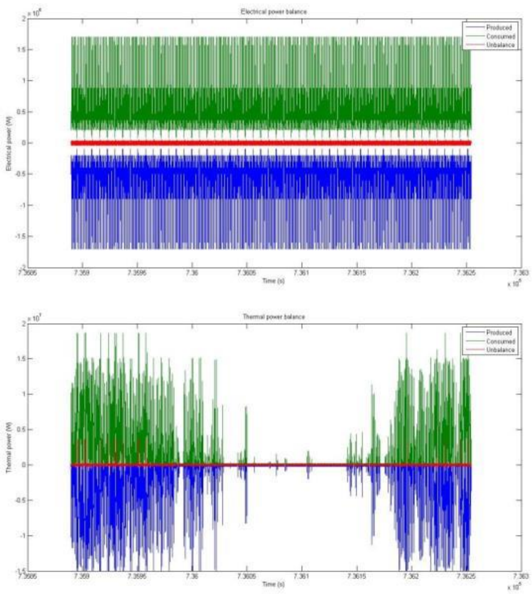


Figure 22: Electricity profile (top) and heat profile (bottom) during the whole year in the BAU scenario of Tweewaters. (blue = production, green = consumption, red = unbalance)

For each case study different kpi’s were produced in order to compare the different scenarios, the most important kpi’s being:

- Electricity and heat demand.
- Electricity and heat generation.
- Electricity grid imports and exports.
- Electricity demand covered by the Grid, RES (Renewable Energy Sources).
- Heat demand covered by RES and REC.
- Use of locally generated energy.
- Primary Energy demand (PE) and associated CO_2 emissions.

As an illustration, Figure 23 shows the monthly primary energy demand in the 3 scenarios for each of the 5 case studies.

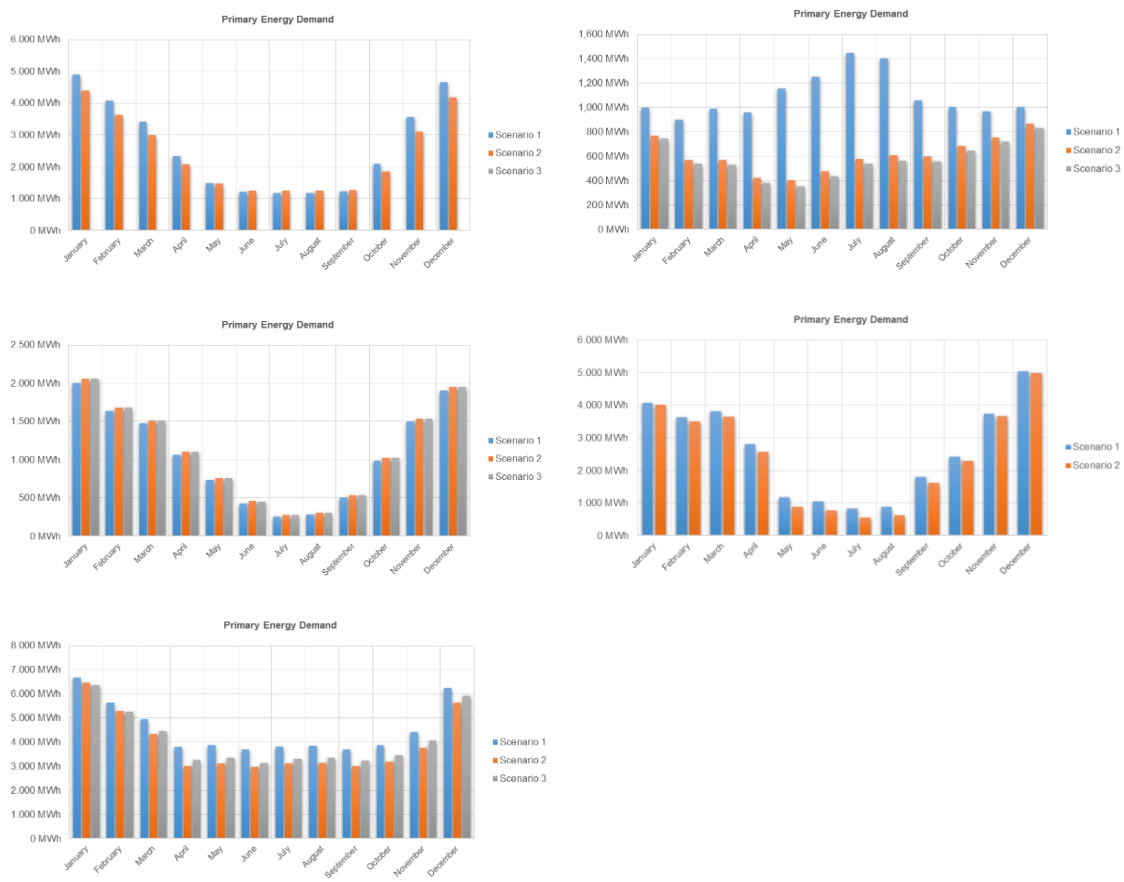


Figure 23: Monthly primary energy demand in the 3 scenarios for each of the 5 case studies: Tweewaters, Houthaven (top), Bergamo, Freiburg (middle) and Dalian (bottom).

The main kpi's for the case study of Houthaven are shown in Figure 24.

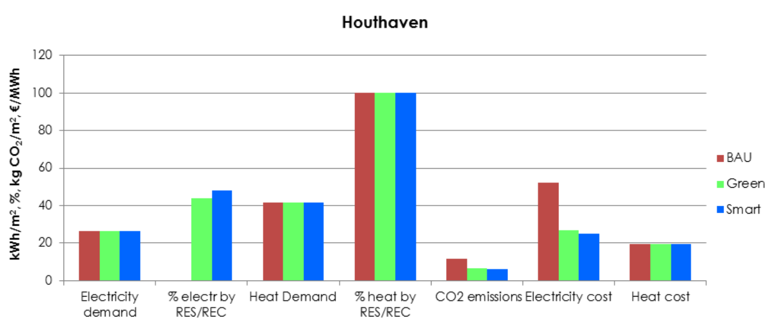


Figure 24: Main kpi's on energy, ecology and economy for the case study of Houthaven, Amsterdam

The introduction of technologies based on Renewable Energy Sources (RES) and/or Recovered Energy (REC) within the district (GREEN/Low Carbon scenario) results in an important decrease in primary energy use and CO_2 emissions and leads to more beneficial cash-flows for the studied cases. Moreover, by introducing smart capabilities (SMART scenario) extra savings in costs can be realized. In the SMART scenario the environmental impact may decrease or increase depending on the business case selected.

In addition to the study of technical issues, an overview is made of the regulatory framework and non-technical barriers and practical guidelines for each of these case studies. Barriers identified include: administrative and legal barriers, economic, financial and market barriers and social barriers and acceptance issues that may hamper, in the short term, the application of the E-hub concepts in real life cases.

2.6 Application of smart energy management in Lab demo

The second application of a smart energy management is the demonstration of the Multi Commodity Matcher in a real lab environment controlling the operation of several cogeneration units. This required producing an interface allowing the communication between the MCM control algorithm running in Matlab and the data acquisition and control system, running in LabVIEW. The equipment controlled included:

- An Internal Combustion Engine CHP (ICE), with thermal/electrical output of 40/20 kW.
- A micro Gas Turbine CHP (mGT) with a thermal/electrical output of 160/100 kW.
- A boiler with a thermal output of 30 kW.
- A 5 m^3 thermal storage vessel.

The thermal load can be controlled independently for each piece of equipment using fan coolers. The electricity demand can be controlled with a controllable resistance bank. Excess of electricity is fed to the grid.

Figure 25: Left: equipment at the lab at TPG-DIME, with a boiler, an Internal Combustion Engine CHP (ICE), a micro gasturbine CHP (mGT) and thermal storage vessel. Right: TPG-DIME personnel at the data acquisition and control system.

The lab demo tests were carried out with and without thermal storage. Both tests were carried out according to predefined heating and electricity demand profiles, shown in Figure 26. For a cogeneration unit, producing heat and electricity at a more or less constant ratio, these are conflicting profiles, for which the control strategy has to find an optimal solution.

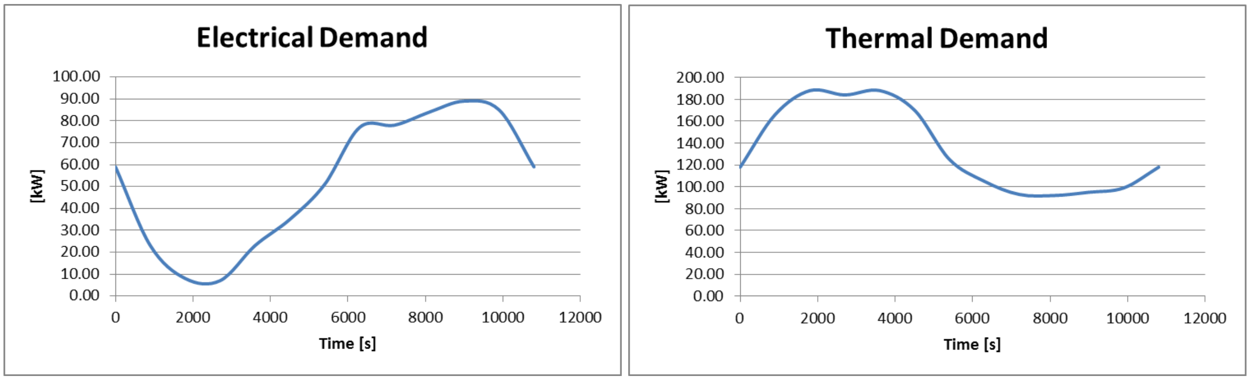


Figure 26: Conflicting profiles: low electrical demand and high thermal demand in the first half of the test and vice versa in the second half.

The results of 4 cases were compared:

1. A *simulation*, using the ECoMP (Economic Cogeneration Modular Programme) software, calculating the economic optimal use of different cogeneration units. This is the reference case.
2. A *real test* in the lab with the Zack algorithm controlling the cogeneration units
3. A *real test* in the lab with the MCM controlling the cogeneration units
4. A *simulation* with the MCM controlling the cogeneration units to check the operation of the MCM

The results of the runs **without** thermal storage are shown in Figure 27 below.

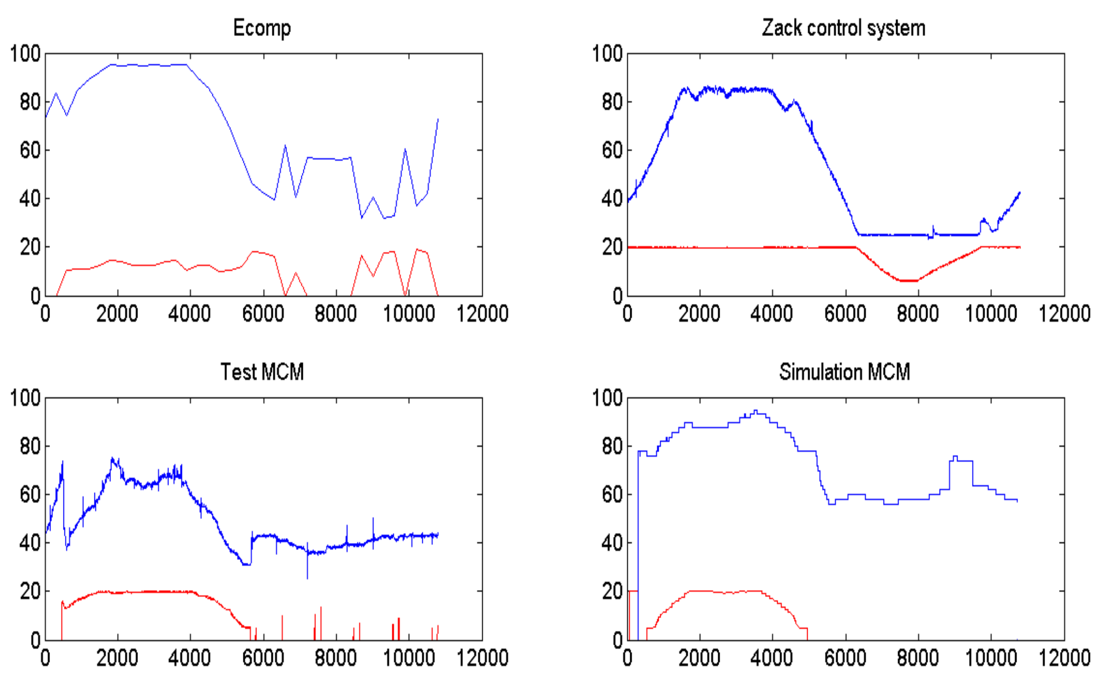


*Figure 27: Results of the 4 runs **without** storage: blue line: output power of the mGT, red line: output power of the ICE*

The graphs of the MCM test and MCM simulation are similar, showing that in a real lab environment, the MCM performs as could be expected. The MCM test and the Zack control test also show similar behaviour. Finally, the shape of the curve is similar to that of the economic optimum given by the reference ECoPM simulation.

The results of these cases **with** thermal storage are shown in Figure 28 below.

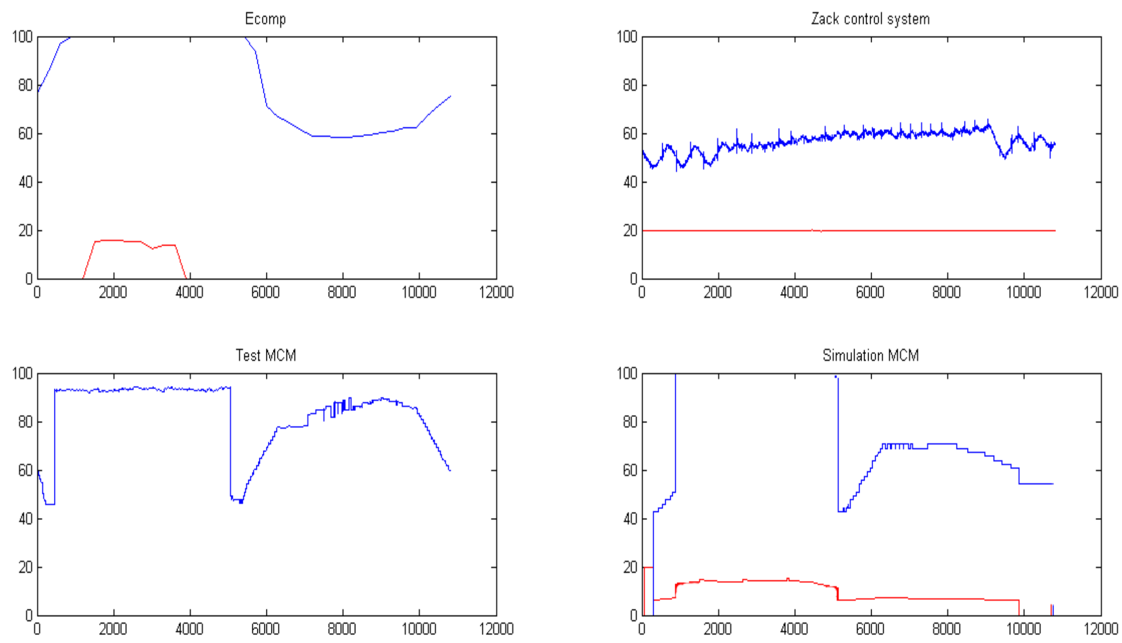


*Figure 28: Results of the 4 runs **with** storage: blue line: output power of the mGT, red line: output power of the ICE*

As in the test without storage, the graphs of the MCM test and MCM simulation are similar, showing that in a real lab environment, the MCM performs as expected. Contrary to the previous test, the Zack control choses a different – non-optimal- strategy to control the test rig. This may be due to the fact that the Zack control was not designed to operate with thermal storage.

Finally, when comparing the MCM (both test and simulation) with ECoMP, the shape of the curves in the first half of the test are similar, showing the MCM comes close to the economic optimum. In the second half of the test, there is a difference between the MCM and ECoMP, due to differences between the actual thermal storage and the implementation of the model of thermal storage in ECoMP.

2.7 Work package 5 Full scale Demonstration

The third application of a smart energy management system (electricity only) is the full scale demonstration in the district of Tweewaters in Leuven, Belgium.

Tweewaters is a unique inner-city development which is one of the largest inner-city developments in Belgium. It consists in total of 1,200 dwellings, commercial spaces, offices and other functions covering an area of 11ha in the city centre of Leuven. Ertzberg's Urban Convenience® vision focuses on the integration and interaction of all aspects of a sustainable quarter (energy, mobility, use of open spaces, waste, consumption of food, etc.). more information can be found at: http://www.tweewaters.be/.

The district is still under development and the first building completed is the 'Balk van Beel' apartment building, housing 106 families and commercial spaces, shown in Figure 29. A smart energy monitoring and control system was installed in this building.

Figure 29: Artist's impression of the Tweewaters quarter, of which the 'Balk van Beel' building has been completed. To the right, apartments on top of the grain silos of the former Stella Artois brewery.

The Balk van Beel was International recognised with the award of the BREEAM ‘Outstanding’ certificate and the 2013 BRE award. The quarter of Tweewaters and its first phase, the ‘Balk van Beel’, received a nomination for the Global Cleantech Cluster Association (GCCA) Later Stage Award and the European Corporate Social Responsibility Award (CSR). Both the building and the quarter are also being used as a model project by Leuven Climate Neutral 2030 and the Flanders in Action (VIA) program.

The energy concept of the Tweewaters district is based on *local production and consumption of green heat and electricity*, using a natural gas fired (later: biomass fired) CHP plant. *Smart control* will be applied to flexible energy sources to match energy supply and demand, to decrease the disturbance to the grid and to enhance the opportunity for green energy production. The integration with a neighbouring district heating network for the sale of heat is taken into account.

An energy consortium between Ertzberg (developer of the quarter and of the smart control of energy), Dalkia (the energy producer) and Eandis (the distribution system operator for heat and electricity) was set up to supply the district with energy.

Over the summer, Ertzberg conducted interviews and workshops with the tenants, in order to report on client behaviour. Privacy issues have been addressed and feedback from the tenants has been reported.

Figure 30: Workshop with tenants from the Balk van Beel demonstration building

The smart monitoring / management system installed in 106 dwellings and 9 commercial spaces in the Balk van Beel, allowed us to produce Profiles of DHW (Domestic Hot Water), space heating and electricity. As an illustration, Figure 31 shows a 3D map of the electricity consumption per hour in the month of April 2014.

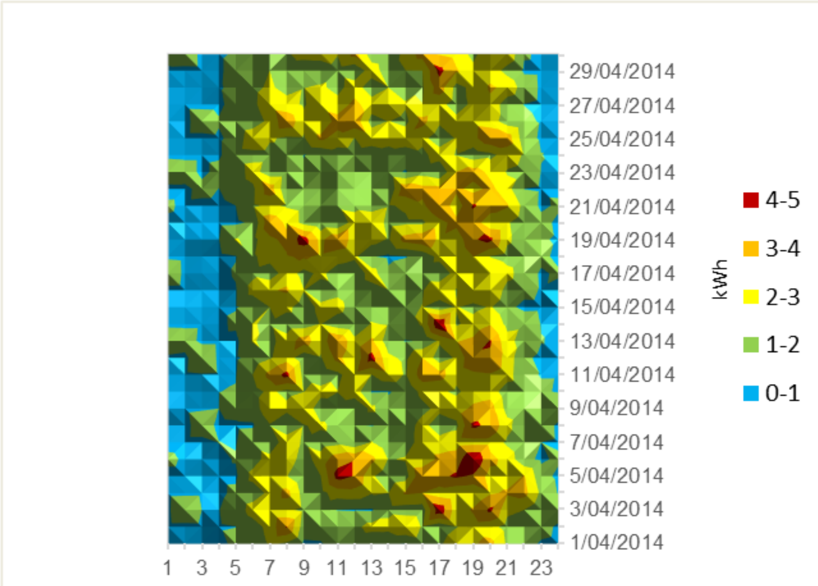


Figure 31: Three-dimensional representation of the electricity consumption of the 'Balk van Beel' in April 2014 in kWh per hour (kW)

The map clearly shows low consumption (blue shaded area) between 23:00 and 5:00. It also shows the higher consumption in the weekends (e.g. 5, 6 April)

The energy demand for space heating in the 'Balk van Beel' ranges from 6 to 26 kWh/m^{2}a, with an average of 11 kWh/m^{2}a. This is better than the Passive house standard of 15 kWh/m^{2}a, showing the high quality of the building.

Regarding the potential of shifting the consumption of household appliances, the rather low amount of smart starts allowed by the tenants does not allow us to draw solid conclusions. In the specific case of Tweewaters, a cost reduction of 20% was achieved compared to the reference scenario. However the mean flexibility of 136 minutes observed in Tweewaters is too low to gain significant electricity cost reductions. For higher profits, the flexibility window should increase to 420 to 460 minutes.

In a simulation, with a smart control of the CHP, operating it at times of high electricity prices, a realistic estimation is that profits from electricity sold to the grid can be raised by 30%. Over a period of one year this results in a profit in the order of 47 € per apartment.

The savings achieved may in themselves not justify the investment in a smart energy system. However, smart control systems are a necessary part of future energy systems to optimally meet all end users' ever increasing energy demands. In the next phases of the development of the Tweewaters quarter, the energy management system will be applied to the other buildings.

2.8 Work package 6 Business Strategies and non-Technical Issues

WP6 provides the basic business information to define alternative energy service concepts and their business concepts as well as implementing them in terms of ‘business agents’.

In the first phase of the project, an overview was made of existing business models from a literature study, 20 case studies by partners and a web questionnaire. The overview also included an overview of barriers and incentives for district energy concepts.

Taking the perspective from an investor to finance an energy efficient district, a number of “Supporting methods and tools for financing energy efficient districts” were identified, through a research activity aimed at:

- Classifying stakeholders according to their financing/investments needs and their role in providing financial resources.
- Understanding the basic features of investments in district heating networks and smart grids.
- Examining existing and emerging models to finance EE/RES projects at private and public level.
- Identifying and discussing 17 relevant best practices already implemented in this field.
- Analysing a set of real life financing case studies, according to criteria such as financing terms, equipment ownership, responsibilities/liabilities of each party, requested guarantees and type of assessment applied by the financier to evaluate the project.
- Discussing barriers and recommendations with relevant financial stakeholders.

Through an extensive research, conducted by analysing existing literature and conducting interviews with financiers, we outlined short practical guidelines for different stakeholders: individual/households, public buildings’ owners, commercial/industrial buildings’ owners and project developers.

A future district is imagined with different groups of energy consumers, producers and “prosumers” (members who are both producers and consumers). On district level, the match between the supply and demand of energy is managed by a “multi commodity matcher” using an automated pricing mechanism. The district is also connected to the national grid, so the national price of energy also affects the price of energy in the district.

The general pricing mechanisms are described. Currently, the marginal price of electricity is determined by demand and supply on national level. In times of a large supply from, for instance, an offshore wind farm, electricity prices on the exchange market will be low (and may even be negative) and in times of high demand, prices will be higher. Balance responsible parties (BRP’s) can trade the energy by day-ahead or by intraday market mechanisms. Currently consumers typically pay a flat tariff, but this is expected to change to TOU (time of use) pricing, critical peak pricing or even real-time tariffs.

Prosumers within the district are assumed to have a certain amount of flexibility in their consumption and production of energy. This flexibility is a new aspect in the energy market. A total of 15 novel business concepts were identified, some of them based on the concept of flexibility of energy demand. They are aimed at various stakeholders such as energy providers, balancing responsible parties (BRPs) transmission system operator (TSOs) and energy producers as well as business models for new roles. A limited number of these were produced in a ‘cook book’ or ‘recipe book’ of novel business models.

To apply the business concepts in our simulation environment, it needs to be translated into a “business agent”. It is also called an “objective agent” because it has the objective of steering a cluster of energy producers and consumers into a different mode, satisfying the demand of a certain stakeholder. For instance when a DSO or BRP needs a higher consumption of energy it may artificially decrease the energy price to promote consumption.

Price manipulation) is typically used in business cases that focus on time of use (TOU) pricing. The objective agent fixes a price on the cluster of devices that reflects the business cost for the cluster operator, e.g. it may streamline the power exchange price from an external market with a customer price to be paid in the cluster. A lower price will lead to higher demand (and lower supply) and vice versa.

Two business agents were produced:

1. time of use/ToU business agent and
2. peak shaving agent, which can also be considered as a ‘reduce imbalance cost’ business agent as they are based on similar principles.

Finally, a qualitative and a quantitative analysis of business models of the five case studies was carried out. The latter is based on the results of the simulations from WP4. The qualitative business models considered are summarized in Table 5 below.

Table 5: Qualitative business models considered in the different case studies

ID	Business case	Twee-waters	Dalian	Hout-haven	Freiburg	Bergamo
BC1	Flexibility for the BRP’s portfolio management (day-ahead)	x			x	
BC2	Flexibility enabling maximised utilisation of locally produced energy			x		
BC3	Flexibility for local network management enabling maximised renewable energy supply		x			x
BC4a	Flexibility for the BRP’s portfolio management (intraday)	x	x		x	
BC4b	Flexibility for balancing services to the TSO (real-time)	x			x	
BC10	Heat storage utilised in district heating and/or cooling		x			x
BC12	Heat recovery of excess heat utilised in district heating and cooling		x			x
BC13	Prosumer selling self-produced energy		x			x

In the qualitative Business model, the roles of the different actors which are part of the energy consortium are given and the business cases which were applied within the different case studies are explained. The information is summarized in a graphical presentation of the business model, showing all actors which are part of the energy consortium and the most important interactions between them. As an illustration, Figure 32 shows the quantitative business model of Dalian.

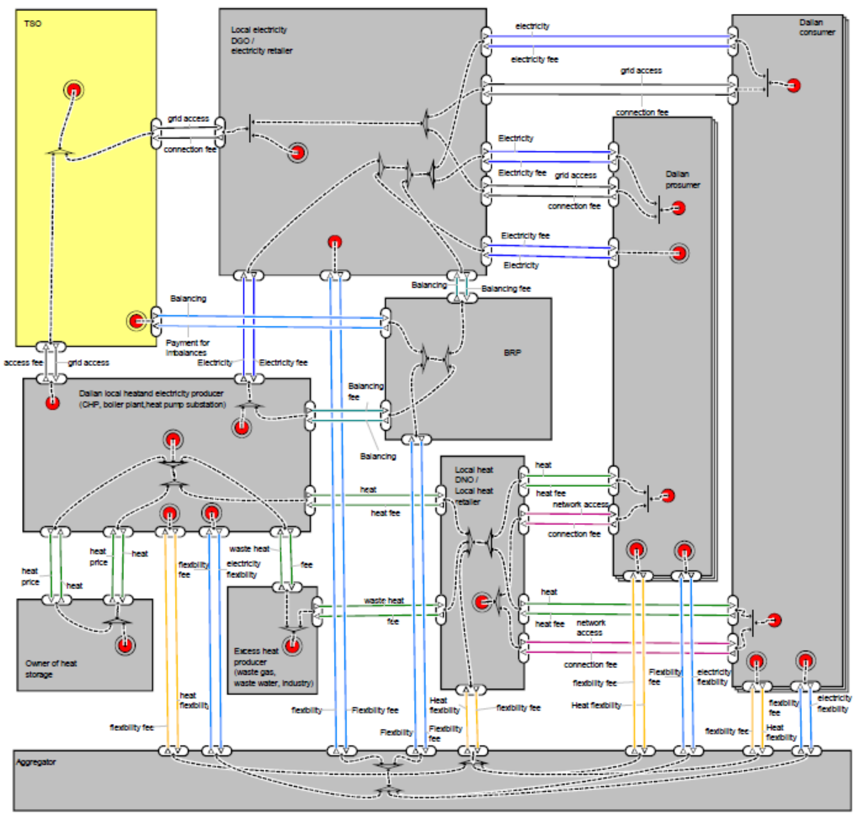


Figure 32: Schematic of the relations between stakeholders in the Dalian case study in E3value

3 More information and relevant contact details.

More information can be found on the public website of the project (http://www.e-hub.org/), For more information please contact F.G.H. Koene, frans.koene@tno.nl.

More information on the Tweewaters inner-city development can be found at: http://www.tweewaters.be/.

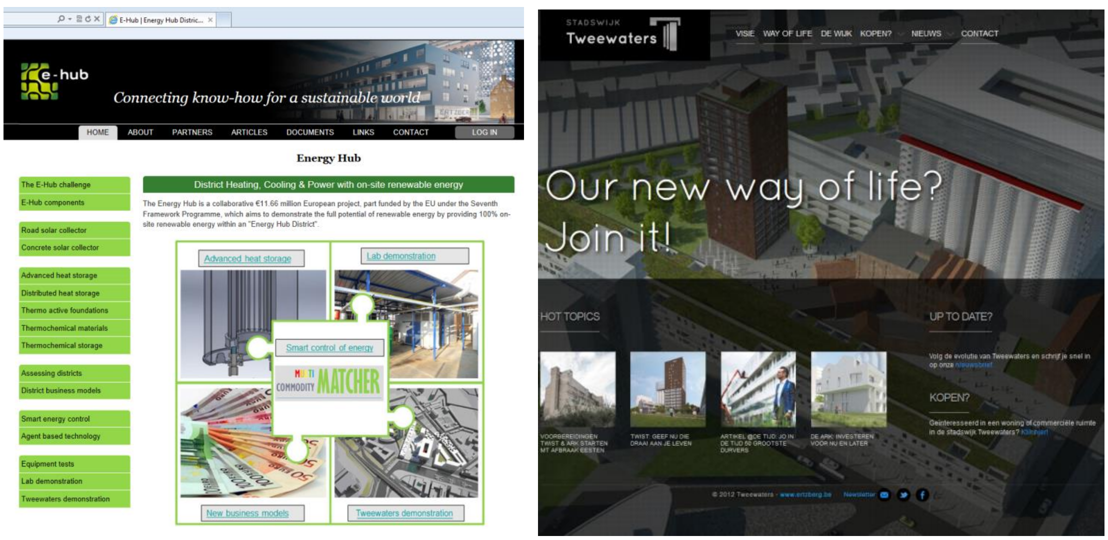


Figure 33: Home page of the E-hub website (left) and Tweewaters website (right).

A glossy brochure was produced, giving an overview of the work in the e-hub project and its application to the full scale demonstration in Tweewaters, see Figure 34 below.

Figure 34: Front page and pages 8/9 of E-hub Glossy Brochure

The brochure can be requested by contacting partner Ertzberg: ive@ertzberg.be or info@ertzberg.be.

In the four years of the project, 6 peer reviewed publications were submitted to scientific journals and 23 papers were written and presented at international conferences. They are summarized in *Table 6* and *Table 7* below.

Table 6: List of peer reviewed publications in scientific journals.

No	Title	Author(s)	Type of activity	year	Reference
1	Plant management tools tested with a small-scale distributed generation laboratory	M. L. Ferrari, A. Traverso, M. Pascenti, A.F. Massardo	Peer review publication	2014	Energy Conversion and Management 78 (2014) 105-113
2	Real-time tool for management of smart poly-generation grids including thermal energy storage	M. L. Ferrari, M. Pascenti, A. Sorce, A. Traverso, A.F. Massardo	Peer review publication	2014	Applied Energy 130 670–678.
3	Should it be automatic or manual - the occupant perspective on the design of domestic control systems	S. Karjalainen	Peer review publication	2013	Energy and Buildings, vol 65, 119-126 (Doi 10.1016/j.enbuild.2013.05.043)
4	Prototype thermochemical heat storage with open reactor system	H. Zondag, B. Kikkert, S. Smeding, R. de Boer, M. Bakker	Peer review publication	2013	Applied Energy 109, 360-365
5	Grey-box model and identification procedure for domestic thermal storage vessels	F. de Ridder, M. Coomans	Peer review publication	2014	Applied Energy (Applied Thermal Engineering) 67 147-158
6	Stakeholder Analysis and Questionnaire Showing the Way for the Development of Business and Service Models	M. Virtanen	Peer review publication	2014	Energy Procedia. 58, 51-57

Table 7: List of presentations at international conferences

No	Title	Presenter(s)	Date	Place
1	Inter project conference	F. Koene (TNO)	09/09/2013	Nice, France
2	Prototype thermochemical heat storage with open reactor system	Zondag et al. (ECN)	16/05/2012	Innostock 2012, Lleida
3	More effective use of renewables including compact seasonal thermal energy storage	Cuypers et al. (TNO)	16/05/2012	Innostock 2012, Lleida
4	Seasonal storage of solar heat: reactor modelling	R. de Boer (ECN)	01/06/2012	av Lorentzen conference, Delft
5	Smart poly-generation grid: a new experimental facility	M. L. Ferrari, et al (TPG-DIME)	11/06/2012	ASME Turbo Expo, Copenhagen Denmark
6	Smart poly-generation grid: control and optimization system	M. Bozzo, F. Caratozzolo, A. Traverso (TPG-DIME)	11/06/2012	ASME Turbo Expo, Copenhagen Denmark
7	An experimental facility for tests on distributed generation Systems	Ferrari M.L., et al. (TPG-DIME)	05/07/2012	international Conference on Applied Energy, Suzhou, China
8	Smart poly-generation grid: experimental setup and control System	Francesco Caratozzolo, et al. (TPG-DIME)	11/09/2012	67° Congresso Nazionale ATI, Trieste Italy
9	An ICT architecture for energy management in district energy systems	M. Hommelberg, D. Geysen (VITO)	05/11/2012	IEEE SmartGridComm, Taiwan
10	Multi-agent control for integrated heat and electricity management in residential districts	Paul Booij, et al. (TNO)	6-10 May 2013	AAMAS - ATES conference, Saint Paul, Minnesota, USA
11	Understanding Local Energy Initiatives and Preconditions for Business Opportunities	Mieke Oostra (TNO), Bronia Jablonska (ECN)	22-24 May, 2013	Sustainable Building 2013, OULU, Finland
12	Innovation in energy efficient buildings and districts for smart built environment	Johan Desmedt (VITO)	26 June 2013	EUSEW 2013, Brussels, Belgium
13	Real-time optimization and experimental validation of smart poly-generation grids with thermal storage device	Mario L. Ferrari et. al. (TPG-DIME)	1-4 July 2013	ICAE2013 (invited for Applied Energy).
14	Simulation of energy conservation measures and its implications on a district heating system: a case study	Mehmet Elci, et al. (Fraunhofer)	26. August 2013	BS – Building simulation 2013, Chambery
15	Simulation framework for simulation and control of a hybrid energy network	Davy Geysen (VITO)	9-11 Sept, 2013	ICT 4 Sustainable Places, Nice (F)

No	Title	Presenter(s)	Date	Place
16	Experimental Results of a 3 kWh thermochemical heat storage module for space heating application	Christian Finck et. al. (TNO)	23-25 Sept, 2013,	International Conference on Solar Heating and Cooling, Freiburg, Germany
17	Thermal energy storages combined with heat and power plants for load management	Andreas Bachmaier, et al. (Fraunhofer)	18. Nov 2013	IRES - International Renewable Energy Storage Conference and Exhibition
18	Simulation framework for simulation and control of a hybrid energy network	Geysen et al. (VITO)	2014	Energycon 2014
19	Plant management tools tested with a small-scale distributed generation laboratory	Mario L. Ferrari et. al. (TPG-DIME)	February 2014	Energy Conversion and Management
20	Simplified building model of districts	F.G.H. Koene, L.G. Bakker, (TNO), D. Lanceta, (SOL), S. Narmsara (Fraunhofer)	sep-14	BauSim 2014 (IBPSA-Germany)
21	State of charge estimation of thermal storages for distributed generation systems	A. Cuneo, M.L. Ferrari, M. Pascenti, A. Traverso (TPG-DIME)	May 2014	6th International Conference of Applied Energy (ICAE), Taiwan.
22	Development of a prototype system for seasonal solar heat storage using an open sorption process	Robert de Boer, Simon Smeding, Herbert Zondag Guido Krol (ECN)	May 2014	Eurotherm Seminar 'Advances in Thermal Energy Storage"
23	Development of business concepts for Energy Hub systems	Sepponen Mari, Heimonen Ismo (VTT)	June 15–19, 2014.	ECOS conference Turku, Finland