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Interaction and integration between buildings, grids, heating and cooling networks, and energy storage and energy generation systems

AMBASSADOR

Autonomous Management System Developed for Building and District Levels

Start date of Project: 01/11/2012
Duration: 48 months

FINAL PUBLISHABLE SUMMARY REPORT

Executive summary

The AMBASSADOR project ended by end of October after 4 years of research on energy for Smart Districts. 15 partners were contributing to the results of the project, with an overall budget of 10 M€, and 6.5 M€ funding from European commission in the frame of FP7 framework.

The major objective of the AMBASSADOR project was to develop energy solutions for Smart Districts, both for electric and district heating networks. In addition to technology developments, works have been dedicated to better capture business aspects, understand who the actors in place are, and what the very first business opportunities that are foreseen.

The overall concept of AMBASSADOR is giving the opportunity to any organization in the District to define and implement optimization strategies serving its business objectives. Depending on the organization profile, the business objective can be energy cost optimization, CO_2 emissions reduction, self-consumption, increased resiliency, or a combination of different objectives.

In addition to the business objective of each single organization, AMBASSADOR has developed a system introducing coordination at district level: the District Energy Management and Information System. The DEMIS coordinates each actor of the district, to implement a new mission for the whole district.

In the very early stages of the project, the business framework was defined providing structural inputs to system architecture and control. In the case of a private campus, all assets and buildings are owned by a single organization. Thus one can concentrate all the necessary knowledge in a single controller which will decide the optimal strategy for the campus. Another business case much more challenging is the “local utility” business case where the system needs to consider multiple organization, without being intrusive. This brings strong constraints to the DEMIS that needs to coordinate sub-systems without any information on the nature of the sub-system.

Solution demonstration and potentials evaluation have been conducted through three demonstration sites and a dedicated District Simulation Platform. The demonstration sites are BedZED in Sutton, UK - CEA Ines in Chambéry, France and the Lavrion Technological and Cultural Park in Lavrion, Greece. The solution has been deployed on two of the demonstration sites. The District Simulation Platform and the BedZED demonstration site have been used through simulation in order to evaluate solution potentials.

The solutions developed within AMBASSADOR have demonstrated that flexibility is key in the process of energy optimization. Flexibility embedded into the systems will be exploited on priority. Heating or cooling in buildings is an example of flexibility that is exploited, without compromising occupants comfort. In the case of electrical vehicles, the batteries combined with the understanding of car usage provide important flexibility for optimization. Finally, when flexibility embedded into the process in not sufficient to reach business objectives, energy storage can be added.

In terms of impact, AMBASSADOR has demonstrated:

- capacity to maximize self consumption of local renewable energy, while limiting peak consumption;
- capacity to define optimal charging schedule of electric vehicle fleet;
- at building level, achievable energy savings ranging from 10 to 40%;
- at district level, 20% of impact on cost thanks to smart algorithms.

AMBASSADOR has also made some recommendations that should contribute to boost Smart Districts deployment:

- price on CO_2, along with energy mix prediction ;
- support self consumption - energy positive districts ;
- support introduction of renewable energy sources and storage for more flexibility ;
- develop the concept of smart grid ready “thing”.

Finally, new business opportunities already emerge for AMBASSADOR industrial partners.

Summary description of project context and objectives

Cities today cover approximately 2% of the earth surface, but create 80% of the global CO_2 emissions. It is globally expected that the world population living in cities will grow from 50% today to 70% by 2050.

Reducing and managing energy consumption at building and district levels as much as possible is a key challenge for the coming years to subsequently reduce the global CO_2 emissions.

To achieve the best results and highest savings, a holistic approach needs to be envisaged starting at building levels then extended at district level, and taking into account all key district players. Solutions to be developed at building level for reducing the energy consumption of the buildings range will come from new concept of HVAC systems and hot water preparation, to management and storage of renewable energy. These concepts will be extended at district level, taking into account all key players, i.e. the energy providers and distributors as well as public transportation. Precise forecast of energy production and consumption, as well as availability of energy storage needs to be established to insure the best usage of renewable energy. To date individual installations for energy generation, storage and consumption are considered separately or with only very limited integration. Therefore, centralized and intuitive Energy Management Systems that can adapt to user and district behaviors are needed. Developing such a system for use in buildings and districts is a very challenging task, due to:

- inclusion of various energy players,
- optimization of energy production and storage techniques,
- the various expectations and acceptances of different types of users.

The EU has set itself ambitious targets to achieve clean and secure energy for tomorrow. An optimal use of available tools is necessary to meet these targets. A wide range of technologies and methods exist to improve energy efficiency, reduce emissions and turn renewable into viable energy sources.
However, the research effort has only concentrated on stand-alone buildings, dependent on their immediate environment. A new approach is needed to achieve the best possible results and highest energy savings starting at the building level and extending to a district level, considering district players.
The purpose of the AMBASSADOR project was to study, develop and experiment systems and tools that aim at optimising the energy usage in the perimeter of a district by managing the energy flows, predicting and mastering energy consumption and energy production. The overall goal of AMBASSADOR was to define and experiment a system that optimises the cost of energy in a district, the cost being expressed in Primary Energy, CO_2 or €. The project investigated energy efficiency both at a building level and at a district level.
The main objectives of the project were:

- To develop a holistic energy optimisation system for a district, taking advantage of the possible shared usage of the local energy production and storage and the complementarity of energy consumption profiles;
- To develop additional management system functionalities to optimise building energy consumption;
- To expose building or technical systems flexibilities to the district;
- To validate through several selected scenarios some functions or services proposed by a DEMIS on the three validation sites (CEA-INES demonstration site – Chambery France, Lavrion Technological and Cultural Park – Lavrion Greece, BedZED dwelling – Beddington UK);
- To study different business models that can be successfully implemented.

These objectives hold several challenges, among them the most evident are:

- Integrate Optimisation technology at the DEMIS level;
- Produce the needed models that will lead to an Efficient Simulation;
- Provide accurate predictions for energy production and consumption;
- Study Energy production and storage equipment and select some to be experimented;
- Define the most generic architecture for the DEMIS.

The crucial element of the AMBASSADOR system is the District Energy Management and Information System (DEMIS). It is the global management component of the system, recipient of the information which runs the global optimisation algorithms. The DEMIS is designed to interact with the technical systems that are able to perform the needed actions on the energy consumption in the perimeter of the district. These technical systems belong to the building level or to the district level. Their role is either to deliver a service to the occupants, to the users of the district or to contribute to the energy management as energy producer or energy storage provider. The DEMIS will be specified and a couple of possible architecture types will be studied during the project course. The different demonstration sites will offer potential variations of architectural solutions. The functions of the DEMIS and its architecture will vary depending on the actual equipment and type of district that is concerned.

Main innovation of AMBASSADOR is seeing the district instead of isolated elements (buildings). This requires some innovations to manage the energy flow between the district elements. Global energy efficiency will be reached by optimising energy fluxes at domestic level but above all by putting in communication all district energy players through a holistic approach. Further activities will make sure that inputs requested by DEMIS and output produced by buildings will be compatible and standardized when possible.

In order to lead the partners to achieve the AMBASSADOR objectives the structure of the work plan was divided into 9 work packages (WPs), each targeting different objectives, tasks and expected results. Out of these 9, 6 were research WPs, one was focused on validation, while one served to manage the project, and the remaining WP dealt with the objectives of outreach, training and exploitation.

AMBASSADOR was coordinated by Schneider Electric Industries. The team was made up of 11 nationalities and integrates the expertise of wide spectrum of professionals and scientist in the field of energy efficiency.

A description of the main S&T results/foregrounds

All results of the project are summarized in the project publications, deliverables and in the AMBASSADOR webpage (http://ambassador-fp7.eu/).

1. Introduction

The pivotal element of the AMBASSADOR system is the District Energy Management and Information System (DEMIS). It is the global management component of the system, recipient of the information and which runs the global optimisation algorithms. The DEMIS has been specified and a couple of possible architecture types have been studied during the project. The functions of the DEMIS and its architecture varies depending on the actual equipment and type of district that is concerned.
The specifications of the system are based on use cases that are expressed in the context of a Business Model whose main characteristics is that energy consumption is centrally managed within the district on a common optimisation goal. The use cases are defined at District level and Building level.
For the use cases at the District level it is considered that the user of the system is a District Energy Manager, each use case illustrates a particular goal. The project has selected the four following ones:

- UC-D1: Optimise the distribution of renewable energy sources
- UC-D2: Optimise the energy costs by managing consumption and sales
- UC-D3: Minimise CO_2 footprint
- UC-D4: Mitigate energy outages

For the use cases at the Building level it is considered that the user of the system is a Building Operation Manager, each use case illustrates a particular goal. The project has selected the three following ones:

- UC-B1: Optimise Building Energy Management
- UC-B2: Minimise CO_2 footprint
- UC-B3: Recognise/Identify subsystem energy profile

The use cases defined are referenced for the whole project and have been used for the detailed design on the work packages WP2 to WP6.
The DEMIS is designed to interact with the technical systems that can perform the needed actions on the energy consumption in the perimeter of the district. These technical systems belong to the building level or to the district level. Their role is either to deliver a service to the occupants, to the users aof the district or to contribute to the energy management as energy producer or energy storage. Let's note that only a subset of these systems has been demonstrated on the validation sites. The list is not supposed to be exhaustive, but the systems listed below are the most common ones and the most representative of what could be found in a real situation.
The following technical systems are considered at the Building level:

- Renewable energy production;
- HVAC-L management systems;
- HVAC Systems;
- Building Heating/Cooling systems;
- Building Ventilation;
- Domestic Hot Water (DHW) systems.

The following technical systems are considered at the District level:

- Renewable energy production;
- District Heating and Cooling Systems (DHC);
- Electrical Vehicle Charging Station;
- Heating and Cooling Storage equipment;
- Electricity Storage equipment.

A management system is generally associated to the technical systems that are considered in AMBASSADOR. These management systems are either specialised systems (like an Energy Storage Management System, an Electrical Vehicle Charging Station management System etc…) or the management is included into a general purpose Building Management System.

The global architecture for the DEMIS system is based on the interaction of a centralised management entity with the different subsystems. The DEMIS is defined as the only contact point with the smart grid. All interaction are supported by open and standardised protocol.
Following chapters have been structured in order to reflect the major steps to be considered when moving towards smart energy districts.

2. Monitoring and control

Monitoring is crucial to understand the context of energy, demand, renewable production, and its relation with usage, occupancy and weather conditions. This encompasses measurement, communication infrastructure, data quality and management.

2.1. Sensors, meters

2.1.1. Environment

The list of required sensors was established based on the monitoring requirements of DEMIS. Based on this list, the installation and commissioning of these sensors was successfully completed and included.

For LTCP demonstration site:

- 20 temperature and relative humidity sensors,
- 26 Occupancy sensors,
- 1 indoor CO_2 sensor
- 1 outdoor CO_2 sensor
- 1 lighting level sensor

For CEA-INES demonstration site:

- INCAS experimental houses
  - Air temperature
  - For air temperature measurement in the houses, we use pt100 sensors (electrical resistance = 100 Ohms for 0° / CEI 751 / NF C 42 330) with solar/thermal protection.
- Weather station
  - Air temperature: thermo-hygro sensor Campbell Scientific CS215
  - Global direct Solar radiation: Kipp & Zonen CMP22
  - Global diffuse Solar radiation: evaluation based on global direct solar radiation measurement

No hazards occurred neither during the installation nor the commissioning phase.

2.1.2. Electricity

Several different power meters were deployed in both sites (LTCP & CEA-INES) to offer real time measurements of electrical consumption as well as power quality monitoring indicators.

LTCP demo site
A total number of 15 power meters were deployed and depending on the exact position of each power meter and after taking into consideration factors such as the ease of installation, required functionalities and residents' preferences, three (3) different types of power meters were selected and installed:

- 6 Schneider Electric PM3255
- 5 Schneider Electric PM850
- 4 Schneider Electric iEM3155

Considering DEMIS requirements these power meters were configured to provide measurements with a fifteen (15) minutes interval.

CEA-INES demo site
To upload energy consumption/production measurement of district components to the DEMIS, data coming from several sensors are provided to the automation server through Labview web services or Modbus connection.

For experimental houses, Electrical Vehicle Charging Station and PV platform power measurement, Solea sensors were used:

- Solea AJ42 three-phase model for I-BB experimental house
- Solea AJ12 mono phase model for I-DM, I-OB, I-MA experimental houses, PV platform and EVCS

2.1.3. Heat networks

BedZED District Heating System is the test site selected for thermal energy flows optimization purposes within the project. Measured data from this test site is needed for two kinds of purposes:

- Developed models validation. In an early stage of the project different models were developed for the modelling of thermal transport in a DH system (detailed explained in D4.4), such as, hot water storage tank, balancing valves, library containing materials properties, pumps, other valves…. Nevertheless, during validation stage two main models were expected to be validated with experimental data in BedZED, boiler model and insulated pipe model, which belong to generation system and distribution system respectively.
- Generation optimized controller development. As explained at section **Chyba! Nenalezen zdroj odkazů.**, xMS based on Model Predictive Control (MPC) has been worked out for the set of boilers already existing in BedZED. Measured data is needed to be used as predictions for the developed controller, and for performance checking.

Regarding **validation works**, the required measurements are:

- Validation of generation system model (group of boilers).
- Flow temperature for each boiler (input temperature to boilers)
- Mass flow rate in boilers
- Gas Consumption
- Main water supply temperature to the DH
- Main water return temperature from DH
- Main mass flow rate in the DH
- Validation of pipe model
- Input and output temperature in one section of the network
- Mass flow rate in this network section

Considering the dynamics of the systems, 5 seconds sample time was proposed for a proper validation of the systems. In this way, any little change in the network can be appreciate and virtually reproduced.

Nevertheless, the final measurements taken are:

- At generation level:
- Flow temperature for each boiler (input temperature to boilers)
- Gas Consumption
- Main water supply temperature to the DH
- Main water return temperature from DH
- Main mass flow rate in the DH
- At distribution level, in a terrace Block D:
- Supply temperature
- Return temperature
- Mass Flow Rate

With these recorded data, the validation of the insulated pipe cannot be done. The values of supply/return temperatures and mass flow rate in a terrace are appropriate for the total consumption calculation in a terrace, nevertheless this information is not enough for validating the insulated pipe model, since there is not available the input/output temperature in a section where the mass flow rate does not change.

In relation to **MPC development**, an approximately one-week acquisition was needed, measuring:

- Main water supply temperature to the DH
- Main water return temperature from DH

- Main mass flow rate in the DH
- Gas consumption during acquisition period

In addition, in order to try to establish the boilers operation strategy (unknown for certainty) the following measures have been performed:

- Mass flow rate at each boiler (not simultaneous)
- Outlet temperature at each boiler

Additional measures would be desirable to derive this strategy (simultaneous mass flow rates, individual gas consumption,…) but at the end, it was not possible to carry them out.

2.2. Communication infrastructure

The Automation Server, is a standard off the shelf product from Schneider Electric Smart Struxure offer. It has been used as a generic gateway for its capability to bind data (variables) coming from low level protocols (BacNet, Modbus, LoanWorks, MBus,), analogical measurement (4-20mA, 0-10V) or dry contacts with high level internet Web Service protocols (SOAP, http requests...). For this project, it was decided to use the Automation Server to call through scripts an http url that pushes data to a WebService that insert data in the AMBASSADOR cloud database.

2.3. Data management

All along the AMBASSADOR project, large amounts of raw data were collected and stored in the AMBASSADOR Cloud database. The raw database is containing more than 155 variables for CEA-INES demo site and more that 300 variables for Lavrion demo site. Each data has been time stamped before being stored. This represented on August 2016 a quantity of 15 520 217 individual time stamped measurements. Based on the dynamics of the energy management, data rate collection was set at a rate of 5 minutes to be able to compute optimized set points each 15mn.

Unlike the simulation environment of the District Simulation Platform where the quality of data is intrinsically guaranteed, quality of the data coming from the field is a key challenge to be able to run algorithms in a real-world demo site. During the project, several issues on data quality needed specific attention of the team. Dedicated VNE toolset has been developed and called each time it was needed to retrieve data for the database.

Time zone: AMBASSADOR demo sites are located in 2 times zones; therefore, it was decided to store data in UTC format. Depending on the sensors (some data were time stamped by the equipment) we had to manage the time difference offset.

Time alignment: When using more than one time series to produce a meaning full result, it became extremely important to align data on a Time reference. For AMBASSADOR, were considered as simultaneous data all data produced in the same 5mn time frame.

Missing data: For many reasons like network communication issues, power outages... it may happen that the data collection of some meters can be interrupted. For short interruptions, missing data was calculated using a basic linear regression. For longer interruptions (several hours) or when missing data could not be interpolated, it became important to setup a data recovery process. For example, at Lavrion demo site a data collection was managed at different level sensor database when available, local database, remote database, AMBASSADOR database, using a manual data recovery process had allowed us to recover some of the missing data by requesting the different systems. In some cases, it had not been possible to recover all the missing data. A predictive algorithm might have been used to compute the missing points.

Outliers detection. In all real-time monitoring system some of the measurements can be corrupted (EMC, Network errors...). It is important to be able to filter outliers. A very simple method, knowing the physical limits of our sensors and meters, is to filtered values that are going above or below defined thresholds.

Data Calibration is another key point. Some of the sensors were providing data in different units (°C °F, kW, Watts...). Those data need to be aligned in a coherent manner.

Because of the cost in term of performance of the VNE phase, we recommend when it is possible to clean-up and align data before being stored (need to be done only one time) instead of cleaning up data afterward each time we are using the data.

The performance of the database system is also key. Database time response needed improvement all along the project in order to avoid overflows in the data communication, and provide reasonable time responses for the reports (HMI).

3. Energy Efficiency

To reduce global district energy consumption and to provide flexibility to the DEMIS, several xMS (eXtended Management System) have been developed, deployed and tested on the demo sites, in the scope of AMBASSADOR.

Providing energy efficiency at building level is a key factor to reduce district energy consumption but it must be done without compromising the occupant comfort. The following BMS have different objectives in terms of energy and comfort performance and use different criteria to evaluate this performance.

Some of them are directly controlling the HVAC/active systems of the building (burner, chiller and fan coils at NTUA demo site) when others are controlling “passive” systems with the double objective to increase comfort without degrading the energy efficiency (Optim Ventil at CEA-INES demo site is controlling the windows opening of the experimental houses).

3.1. Building management system

A dedicated Building Management System (BMS) has been designed and deployed in the administration building of the LTCP Park. Due to the fact that the administration building is considered as a cultural heritage building, the design team has given specific consideration on designing a prototype BMS with the minimal interference with building aesthetics. In order this to be achieved, the design team proposed the use multi-purpose management devices which can have a wireless bilateral communication with sensors and controllers.

Briefly, the deployed Building Management System included:

- 16 room sensors (Temperature, humidity, occupancy sensors) & controllers (set points actuators)
- Light switches on/off counter
- 4 water temperature sensors
- 4 two-way valves
- Current switch for burner
- 6 Multi-Purpose Manager (MPM)
- 1 Automation server (AS)

The deployed BMS offers to the building manager advanced functionalities that can improve significantly the building performance of the building by efficiently controlling the HVAC systems (burner & chiller) operation as well as by monitoring the lighting operation within the building and thus propose behavioural change actions.

On this point, it needs to be mentioned the fact that the residents of the administration building showed to be reluctant on following the proposed by the DEMIS HVAC operational schedule (both time schedule and set points) even though the applied set points were well inside the comfort zone range. They appeared eager to change manually and regularly the set points of the fan coil located in their office and not follow the ones proposed by the DEMIS. Probably the incentive of following a proposed schedule by DEMIS should be accompanied with some direct rewards to the employees who do follow as the electricity bill is paid by the managing authority and they do not see any gains for their compliance. Therefore, in the cases of office buildings or other buildings where the financial incentive of reduced electrical bill is not applicable for the residents, the possibility of DEMIS to be intrusive may have to be considered.

3.2. NOL (Neurobat Online)

Neurobat had developed an adaptive model-predictive controller for space heating in residential buildings. During the AMBASSADOR project, those algorithms have been extended to the problem of the optimal control of ventilation and air-conditioning (VAC) systems. Due to the increased computational burden, these algorithms cannot easily be made to run on embedded systems and have been deployed as web services.

The communication between the local controller (BMS in this diagram) and the optimisation server is mediated by a gateway, i.e. a cheap embedded PC whose only responsibility is to pass data between the BMS and the server.

The model-predictive controller for VAC systems works by regularly minimising a cost function over a receding control horizon of two hours. The cost function is a trade-off (controlled by a parameter λ) between the user discomfort (taken as the root-mean-squared error between the indoor conditions and the user setpoint) and the economic cost for processing the outdoor air to the desired condition.

Simulations have shown that the customer can tune the trade-off between user discomfort and economic cost, by adjusting their relative importance in the cost function. It thus becomes possible for the customer to control how many of his users will feel comfortable, and at what cost.

4. Components for predictive control

Predictive controls are technologies that have been extensively used in AMBASSADOR. Those technologies exploit predictions of the near future, in order to decide how the dynamic systems need to be managed. A few analytic bricks and components are required to implement those solutions. In this chapter we provide some performance results on those analytic bricks. We are also presenting here results obtained on other essential bricks dedicated to optimal energy flows management: energy production and storage.

4.1. Prediction

Prediction is essential to predictive control. Both energy demand and production need to be predicted, especially when it comes to intermittent energy sources such as PV.

The prediction models used by the optimization predict the behaviour of the considered element over a 24-hour horizon with a time resolution of 15 minutes. The modelled elements include consumption and production. Renewable production elements include photovoltaic panels (PV) and wind turbines (WT). Prediction components of renewable productions implement support vector regression (SVR) between input conditions (e.g. weather conditions such as solar irradiance or wind speed, and a time frame) and produced power over the last 4-7 days for the SVR training period. Then the energy production over the next 24 hours' production is predicted based on weather forecast and a time frame.

Energy consumption elements includes Lavrion data center, chemical plant, administrative building and cafeteria. Prediction components of consumptions elements implement SVR between input conditions (e.g. weather conditions such as outdoor air temperature, time frame, occupancy/working schedule, process planning) and consumed power over the last 4-7 days for the SVR training period. Then the energy consumption over the next 24 hours is predicted based on weather forecast and a time frame (with relevant available schedules).

4.2. Models

Important developments have been carried out regarding assets, buildings, and district modelling. Those models are required to determine the relation between provided service, energy consumption / production, and KPI's that might need to be monitored (CO_2, cost...), considering environmental conditions, typically weather.

When applicable, the models also give access to setpoints that will be later exposed to the optimization algorithms.

The optimization solution developed in AMBASSADOR requires models of the various process that will be used to forecast production/consumption and define the best strategy on a given time horizon. For some assets, a physical (white box) model can be used. But in most of the case, such model is not readily available or even usable. This can be due to the difficulty to get the value of some parameters, to a model complexity that do not comply with the requirement of the optimization algorithm or to the fact that the asset behaviour is not fully described by a simple physical model. For these reasons, the physical models are often replaced by grey box or black box, reduced model. Such reduced models raise several interesting challenges like finding the right complexity of model, parameter calibration, noise management and auto-adaptive features.

In AMBASSADOR, we face this problem of model complexity mostly for two components: the building and water distribution networks.

For the water distribution network, the challenge is to build a reduced model that will still be representative of both the (flow, pressure) equilibrium and the delay in heat propagation in the network. The very simple model proposed at early stage (derived from building simulation) does not consider these phenomena and was not considered sufficiently representative. Complete model based on Modelica library was too complex to be used in an optimization loop. An intermediate solution was evaluated, without being stable enough for the dynamic control of small networks such as BedZED network. Still this model could be relevant for larger districts where time response is more compatible with energy optimization. In the case of BedZED, it was decided to focus on heat production, and it needs to ne noted that in many cases, the focus will be optimization of heat production, and optimization of heat demand.

Concerning building, detailed modelling was developed using IDA-ICE, but, as for Modelica, this simulation cannot be embedded in an optimization loop. So, for Schneider Electric Building Optimizer, reduced models were developed, using simple transfer function to model each thermal zone and a very simple "global efficiency" of the HVAC production system. A nearly automatic process was developed to quickly produce the model based on either detailed simulation or real data.

Evaluation of models and optimization on the District Simulation Platform allows detection of several faults. Some were corrected while others, like the auto-adaptive feature, are still under development. Poor modelling of the HVAC system was clearly one of the main problems faced. At the detailed model level, each different HVAC architecture will be modelled and simulate using component and control libraries. To convert these architectures into reduced model fitting with the optimization solver constraint is time consuming and will probably be only done for very repetitive HVAC systems.

Apart from the issue inherent to the proposed reduced model, we also faced in AMBASSADOR a number of issue related to the input (data monitoring, see Chapter 2.3) and output control set points of the building optimizer that might in some cases prevent us to use them efficiently to optimize the building assets.

To evaluate the energy performance of our solutions, we need to compare result with and without optimization. This is very difficult to do it in real life as it requires the two algorithms to be tested in the same condition (weather, occupancy...). A common turnaround is to evaluate the performance by using the reduced model to run two simulations. This leads to overoptimistic performance evaluation as it assumed that the model is perfectly representative of the real world. This is why it was decided to develop the District Simulation Platform that embeds the optimization algorithm (with their reduced model) and confront them to more accurate representation of the real physics (we call them the simplified model).

4.3. <u>Flexibility</u>

In the process of energy flows optimization that will be detailed in next chapters, flexibility is key. Indeed, deciding the best strategy for energy management, supposes that options are available in the way energy is consumed, produced or stored. When system process is able to provide flexibility, without impacting the expected service, optimization will exploit this low cost flexibility. In the case where this flexibility is not sufficient, we might need to add more flexibility. Energy storage is foreseen as an important ingredient in increasing system flexibility.

4.3.1. Leclanché

For AMBASSADOR project, Leclanché provided a battery with the following features:

- 25kW/25kWh based on LTO technology
- An interface to be easily controlled
- A system which helps to remotely check/monitor the battery

- A matlab simulation model to be used inside the DSP
- A xMS to ease the integration
- Manage the installation inside the demo site
- Provide support, training during project lifetime

The project was an opportunity to work together with the other partners to solve the problems linked with this kind of system:

- Selection of a location
- Give guidance to the customer to build a local infrastructure needed to operate the system (Power Lines, Ethernet cable, rescued power supply…)
- Selection of means for maintenance
- Provides methodology so the system could be easily integrated platform to user

Inside DEMIS, the system is controlled through an automation server.

4.3.2. Lavrion

A grid-tied hybrid solar system has been designed and deployed in the premises of LTCP. This PV-battery system serves the electrical needs of the administration building. The hybrid system consists of a PV array of 15,39kW and a battery bank of 1364Ah in close proximity to the administration building so as to minimize cabling costs and losses.

The flexibility of the deployed hybrid system derives from the fact that managing algorithm can calculate the optimum energy flows between the administration building and the hybrid system by dictating the optimized operation of the three (3) power sources of the system: Solar PV arrays; Battery bank; AC connected from Building, and thus minimize the cost of energy for administration building owners.

4.3.3. Zebra

Zebra container is a storage system constituted of several batteries pack “high temperature” (NaNiCl technology) with a total capacity of 130 kWh. These batteries pack are coupled with bi-directional inverters of 60 kW each for charge/discharge.

To re-equilibrate the batteries pack, Zebra container must be locally controlled by its own automation every 60 hours. In the scope of AMBASSADOR, it implies that the DEMIS is not allowed to control the storage system during this process. As it was too complicated for the DEMIS to manage this constraint, we have decided not to consider this storage system for district optimization on CEA-INES demo site.

4.3.4. H_2

The inherent intermittent nature of the RES causes a temporal mismatch between electrical energy production and building energy demand profiles. In this frame, hydrogen has been examined both as an energy storage medium and as a green fuel as it presents significant advantages compared to conventional solutions such as the high energy density by mass and the fact that when burnt, the only by-product is water.

In the framework of AMBASSADOR a hydrogen energy storage system was evaluated for an office building application of ≈500 m^2 located in LTCP Greece so as to assess its technical and economic feasibility.

During system testing a number of technical issues have occurred affecting its harmonious operation. These technical issues were mainly caused due to the shutdown of systems’ components (water de-ionizer, electrolyser, hydrogen purifier, fuel cell, hydrogen burner) for a period of 3,5 months. Starting from a malfunction of water’s demineralization system (failure of electrical conductivity sensor), water with conductivity of 2,3μS/cm (1μS/cm max manufacturer specification) was fed the Fuel Cell affecting the proton exchange membranes of the two fuel cell stacks and causing instability to the Fuel Cell operation. Due to the limited production and small availability of fuel cell spare parts, these malfunctions led to very limited available period for system testing and evaluation.

Currently, the technical limitations have been identified and overcome while the first series of uninterruptable tests have been started. Despite the aforementioned shortcomings, this process has contribute significantly on identifying the limitations of hydrogen as an energy storage solution for building applications, highlight the inherent complexity of such systems and propose solutions for future research activities as well as for commercial applications.

5. Energy flows optimization: campus use case

Energy flows optimization can be implemented as soon as some kind of flexibility is present in the system. As mentioned earlier, this flexibility can come from the process itself (temperature range in a building), from alternative controllable energy sources, or form energy storage.

Prediction of energy demand or production will be used with the models, in order to evaluate system performance with respect to business objective.

Then, optimization will consist in deciding how flexibilities need to be operated in order to maximize business objective while respecting operation constraints. Depending on the organization looking for optimization, objectives will defer: cost optimization, CO_2 emissions reduction, resiliency, self consumption...

Last thing is the constraint brought by the actor scenario. In case of a single actor (private campus business case), optimization can be achieved in a centralised manner, by a single controller. In this case, all information, data, and models can be made available to this controller. In this chapter we present results applicable to the campus business case. We also present results on district heating that to some extent can be considered as a system managed by a single organization.

5.1. District heating

BedZED District Heating System is the test site selected for thermal energy flows optimization purposes. As said before, this site is considered equivalent to private campus business case since the whole facility is owned and managed by a single organization (some kind of dwelling owners partnership). On one side, data acquired from this facility has been used to validate developed thermal models, especially those corresponding to distribution pipes, which is one of the key component in this kind of installations (thermal losses, significant thermal delay, etc.). On the other hand, acquired data has been used to characterize the system operation conditions, and coming from this, improvements focused on efficiency enhancement have been analyzed.

5.1.1. Efficiency enhancement analysis

For this analysis, work has been focused on district heating generation plant, leaving aside the distribution network and consumers dwellings. More detailed information about BedZED facility can be found at deliverable D4.4.

At this facility, heat generation is carried out by three identical condensing boilers in parallel arrangement. Each boiler has its own pump, which works at constant speeds (manual selector with three available positions/speeds). From the assessment of the system (including an on-site identification visit), it is established that the most representative pressure loss seen by each pump is that of the corresponding boiler, and thus that the mass flow rate through the boilers should be quite constant.

Regarding generation control, it is observed that a global control is available but not used, so **boilers are controlled individually** through each partial load to achieve an outlet temperature constant reference established at 82ºC.

However, when analysing the data acquired on-site (six months after on-site identification), different behaviour than expected is observed. Mainly:

- Mass flow rate is not constant at two of the boilers. None of the values (or mean values) correspond to those calculated according to pump and boiler curves.
- Boiler outlet temperature never reaches the reference value (82ºC) in any of the boilers

Following these divergences, a new on-site visit was conducted and it was checked that the position of the pumps had been changed and that some installation components were not working properly (at least pressurization system and some filters). These and other findings have brought to light the communication issues between system operators, designers and equipment owners. Because of this situation, *the current operation of the system is unknown* for any of the actors (no change tracking).

Considering this situation, optimization work has been done based on some assumed but **realistic operation cases** considering the existing installation scheme:

- The same mass flow rate through each boiler, equal to boiler nominal mass flow rate (boiler data sheet).
- Different constant mass flow rates
- The same variable mass flow rate (bypass removed)

For each of these cases, a Model Predictive Controller (MPC) has been developed. This controller will adopt the supply thermal power to the district heating distribution as a prediction (values known in a 24h horizon), assuming the measured district heating mass flow rate, return temperature, and supply temperature as predicted values. The developed controller acts as a generation xMS + local controller, obtaining signals for each boiler's on/off and partial load values coming from the thermal demand prediction. The target of the MPC is maximize generation efficiency (minimize boilers consumption).

$$Minimize \rightarrow \quad \sum_{j=1}^{hp} {C_{fuel}}^2 \qquad \textit{hp = prediction horizon (24h)}$$

$$subject\ to \rightarrow \quad \begin{cases} 0 < \delta < 1 \\ \rho_{min} < \rho < 1 \end{cases}$$

$$where \rightarrow \quad C_{fuel} = f\left(\rho_i, \delta_i, T_{supply}, \dot{m}_{DH}, T_{ret}\right) \qquad \textit{i = 1, 2, 3 (number of boilers)}$$

Previous equations show the optimization problem to be solved by the developed MPC. The function to be minimized represents the total cost of the **fuel consumed by the boilers all the horizon time**. A special feature is that a Boolean variable δ is introduced to establish the on/off state of each boiler, which conditions the optimization solver selection. The cost of the fuel depends on the state of each boiler (δ_i), its partial load when working (ρ_i), supply temperature to the DH system (T_{supply}), mass flow rate through the DH system (m_{DH}), and return temperature from the DH system to the boilers (T_{ret}). Partial load an on/off of boilers are the <u>control variables</u>; the supply temperature to the DH system is the <u>forecast</u> to be fulfilled; and the mass flow rate and return temperature are <u>measured data</u>.

For the assessment of the new controller actuation, simulations have been carried out for each of the assumed operation cases using data acquired in BedZED. This data corresponds to a week of system operation and includes gas consumption during that time.

5.2. <u>Explicit optimization</u>

The explicit optimization works at district level by aggregating all consumption/production forecasts and finds the optimal set-points for the flexible elements, in the present case flexibility is provided by batteries. The prediction algorithms employed by the xMSs (or eNodes) are the ones presented in Chapter 4.1.

Simulations were carried out under various conditions: In particular, various tariffs were tested and with various controllers.

It can be observed that the explicit optimization efficiency greatly depends on the boundary conditions. But it is generally better than a storage controlled by a simple algorithm (self-consume and store overproduction). The developed methodology can also allow to drastically reduce the battery size. Indeed, it can be observed that the size in this case could be reduced from 25kWh to 10kWh by impacting the overall savings (w.r.t. the simple battery controller) by only a few percent.

6. Energy flows optimization: facility use case

The key concept of the energy management control approach in the AMBASSADOR project is that a global optimization in the smart district should be achieved using distributed control strategies. The motivations for this choice are manifold:

- <u>Privacy:</u> The assets in the district may be owned and operated by different legal persons who would not be willing to outsource the control of their system (e.g. a building or an electric vehicle charging station) to a global control unit managing all assets of the district in a same instance.
- <u>Scalability:</u> Model Predictive Control (MPC) has been considered to be the most adapted control method to improve the energy efficiency in smart districts and was chosen for this reason. Since this technique relies on continuously solving relatively large optimization problems, it would be

computationally intractable to englobe the control of all district assets in a single optimization problem formulation.

- Modularity: Changes concerning a single asset in the district only concern its local MPC controller and do not have any effect on the smooth operation of the other systems.

In the following two sections the proposed distributed MPC methods as well as simulation results obtained by coupling the latter with the district simulation platform (DSP), are presented.

6.1. Distributed MPC using primal and dual decomposition

The idea of the proposed approach is to apply primal and dual decomposition methods in order to distribute an initially centralized MPC (Model Predictive Control) controller into several local MPC controllers (one for each asset in the district) and into one coordination controller, called DEMIS (District Energy Management and Information System).

Recall that the principle of MPC is to take a control decision at a given time instant by computing the optimal control trajectory for a certain prediction horizon. This way future events can be anticipated very well, provided that a sufficiently precise system model as well as forecasts of exogenous variables (weather forecast, building occupancy forecast,…) are available. Typically, in smart grid applications, a prediction horizon of 12h-48h is chosen. Moreover, MPC relies on a discrete state-space model, meaning that the prediction horizon is divided into discrete time intervals.

In the AMBASSADOR project a 24h prediction horizon has been chosen, which is sampled at a time step of 15min.

Primal vs. dual decomposition

Both approaches, primal and dual decomposition, rely on the idea that an iterative information exchange between the DEMIS and the local MPC controllers allows to recover or at least come close to the globally optimal control that would also have been obtained with the theoretical centralized MPC controller.

One key difference between the primal- and dual decomposition approach lies in the information which is exchanged between the DEMIS and the local MPC controllers:

	DEMIS → local controller	Local controller → DEMIS
Dual decomposition	**Virtual price profile**: This profile is added to the actual price profile in the local MPC controllers, pushing them to modify their behavior in a way that enhances global optimality	**Optimal objective value:** The optimal cost value computed by the local MPC controller. **Power consumption profile**: The predicted power consumption profile which is part of the solution of the local MPC problem.
Primal decomposition	**Power profile**: For each local MPC controller, the DEMIS proposes an individual power profile. For the proposed resource allocation, the local MPC controller computes the optimal utilization that minimizes the local cost function.	**Gradient profile**: The gradient profile of the optimal cost value with respect to the allocated power profile. This rather technical variable is in fact the reduced cost which is directly available in the solution of the local MPC problem.

Why is a global coordination useful/necessary in smart grid energy management applications?

In a first step one might assume that it is sufficient to only have local MPC controllers which aim at minimizing the energy cost of each sub-system based on the energy buying- and selling prices.

However, there are two reasons why this is not sufficient:

- Since local distribution grids have not been designed for the rapidly changing energy landscape (more and more renewables and a foreseeable increase of the electric vehicle penetration), capacity limitations of certain distribution grid components (cables, transformers) may not be respected anymore, if all district assets are operated independently. This is the first reason that motivated the proposed coordinated control approach which relies on the DEMIS to set the necessary incentives for the sub-systems such that the limited transformer/cable capacity connecting the smart district with the external grid is respected.

- For political and economic reasons it is desirable to enhance the energetic independence of local distribution grids from the external grid. By better matching electricity consumers and producers within the smart district, the electricity exchange with the external grid can be reduced importantly. This objective is referred to as the "auto-consumption".

Which one of the two proposed distributed MPC frameworks is preferable?
There is unfortunately not a clear answer to this question. Both, primal- and dual decomposition have their advantages and drawbacks which have to be considered to make the appropriate choice.

	Dual decomposition	Primal decomposition
Advantages	**Exchanged information:** The exchanged information between the DEMIS and the local MPC controllers (virtual prices & power profiles) are more appealing in an economic optimization context, since the virtual prices have a direct economic interpretation. **Scalability:** The complexity of the coordinator problem is lower, since the same virtual price profile applies to all local MPC controllers. In fact, the number of variables in the coordinator problem is independent of the number of sub-systems, meaning that the computational burden is does basically not increase with the number of sub-systems.	**Coupling constraints:** In contrast to the dual decomposition approach, the coupling constraints, i.e. the global limitation on the consumed power from the external grid, is respected at each iteration. Even if the algorithm hasn't converged yet, because the number of performed iterations was not sufficient, the obtained sub-optimal solution still guarantees the coupling constraint satisfaction. **Convergence:** Primal decomposition is not limited to strictly convex optimization problems. Instead, convergence of the algorithm is guaranteed for any convex optimization problem. This rather technical advantage over the dual decomposition framework may save a lot of algorithm tuning time when putting the solution into place. From a practical point of view, any linear programming formulation of the local MPC controllers is suitable, while for the dual decomposition framework, additional quadratic terms would have to be added to enhance convergence.
Drawbacks	**Convergence & coupling constraints:** To guarantee that the iterative algorithm converges towards the global optimum the local MPC controllers are restricted to be strictly convex optimization problems. This requirement is not naturally fulfilled when formulating the economic optimization problems for the different sub-systems. As a consequence, it can happen that the global capacity limitation for the consumed power in the district is not respected. In fact, in dual decomposition, coupling constraint satisfaction is only guaranteed if convergence to the global optimum has been achieved. Nevertheless, it turned out that a convenient calibration of some additional regularization terms in the local MPC problems were able to solve this issue. However, tuning these	**Scalability:** Since the number of decision variables in the DEMIS problem increases linearly with the number of local MPC problems, the primal decomposition approach scales worse than the dual decomposition one.

	regularization terms is not a trivial task and a careless choice may either lead to a bad controller performance or not result in the desired guaranteed convergence.	

In the following section simulation results are presented which show the potential benefits of the proposed distributed MPC frameworks.

6.2. Section presenting the results obtained with the virtual district

The concept of virtual district is proposed in the AMBASSADOR project for the following usages:

- To validate the comprehensiveness of the global optimization approach.
- Performance comparison for different control strategies.
- To study the effects of external inputs like price profile, weather profile, etc.

Location and Scale of Virtual District
Berlin in Germany is chosen as the physical location of the Virtual District.

The Virtual District is designed to accommodate around 2000 residents distributed in collective and individual residences, offices, school and library. It is assumed that during the week, in the daytime, people work in offices, library, school and a small part stay at home. At night and during the weekend, people are in the collective and individual residences. For each kind of building, a simplified model has been used to generate the typical consumption profile. These profiles are then multiplied by a coefficient to obtain a realistic annual consumption for this district size.

The site is equipped of one electric vehicle charging station with 60 charging points, a public lighting, a photovoltaic (PV) and storage systems. The component sizes are chosen to have enough PV and battery to take advantage of the optimization algorithms. The PV size is fixed at 5 MWp to have periods with over-production usable to charge the battery. The battery size is fixed at 7 MWh which corresponds to 10 hours of autonomy with a mean power of 700 kW (mean load power during the night).

The battery is essential for district optimization due to its flexibility to charge and discharge at any time. In the next studies, a focus on the battery management is done. All the district consumption (buildings, electric vehicle charging station and public lighting) are aggregated and considered as one dummy load. The objective is to see how the battery is managed according to the load consumption and the PV production.

Electricity price
The electricity price is initially set to be simple for the ease of validating the optimization algorithms for minimizing the energy cost. It is based on a daily schedule with three levels of price: 6 c€/kWh during the night, 12 c€/kWh during the day and 40 c€/kW during peak hours. The peak hour is from midday to 3 p.m.

Control strategies
To evaluate the potential of the AMBASSADOR approach, this one is compared to others simple control strategies. All the used strategies are described below:

- Standard: The standard mode is used to calculate the reference consumption and electricity cost. The battery and its management are not considered. The results are used to see the impact of the battery addition managed by a simple control strategy like the Smart V1.
- Smart V1: This mode consists in controlling the battery using instantaneous expert rules. At each time step, the battery control set-point is calculated according to the district energy balance (sum of production and consumption). If the PV production is higher than the consumption, the over-production is stored in the battery. But if the consumption is higher than the production, the battery is discharged in order to reduce the consumed energy from the grid at zero. The following figure illustrates the corresponding behaviour. The first graph represents the energy balance without (in red) and with (in blue) the battery. The second and third ones are the battery power and state of charge. The energy balance is positive when the power is consumed from the grid and negative when it is given to the grid. As it is possible to see, the battery is charged using the over production until it is fully charged. Then, when the consumption is higher than the production (energy balance positive), the battery is directly discharged until it is empty.

- Smart V2: This strategy is also based on instantaneous expert rules. In that case, the battery control set-point is calculated according to the district energy balance, the electricity price and the battery state of charge. The objectives are to maximize the auto-consumption and minimize the energy cost. At each instant, if there is over-production, the battery is used to store it but if there is more consumption than production, the battery management depends on the electricity cost and battery state of charge. Globally, the battery is charged when the price is low and discharged when it is high.
- Dual: This strategy is the dual decomposition described in the previous section. In the case of the Virtual district, three xMS are used: one to predict the PV production, one to predict the load consumption and one to manage the battery. The CSEM algorithms are used for the power prediction. The Schneider Electric battery management system is used to control the battery.

Results

For the Dual mode, two simulations with different prediction algorithms are realized: one with the CSEM algorithms and one with a simple algorithm which predicts the power based on known profiles and gives perfect forecasts. These two versions allow comparing the impact of the forecasts quality.

In the standard case, 64% of the consumed energy is extracted from the grid. This represents an annual cost of 590 750 € which can be considerably reduced with the usage of battery. According to the control strategy, the cost savings are between 17% and 37%. In the simplest case (Smart V1), the control strategy objective is to maximize the auto-consumption without considering the electricity price. For this simple district configuration, it is the most advantageous strategy in term of renewable energy penetration. Only 51% of the annual consumption is extracted from the grid. For the Smart V2 and the Dual strategies, the energy consumed from the grid is higher but the battery is used during periods most profitable for the cost reduction. Generally, the energy is consumed from the grid during the night, when the electricity price is low. During the day, the energy is as much as possible provided by the PV and the battery. The Smart V2 approach, based on instantaneous expert rules, reduces the electricity cost of 28% compared than Standard case and 13% compared to the Smart V1 case. The Dual strategy is the most profitable for the cost savings. According to the forecasts quality, the reduction varies between 20% and 25% compared to the Smart V1 case. The Dual mode with prefect forecasts is an ideal case. It gives an idea of how much savings are possible to be reach with the DEMIS and the battery management. In the next studies, only the case with perfect forecasts is used for the Dual mode.

Compared to the Smart V1 strategy, the Smart V2 and the Dual allow considerable reductions of the cost but not throughout the year. As it is possible to see in the next figure, the energy cost is mainly reduced during the winter period. In summer, the PV has the highest production in the middle of the day which is also the period where the electricity price is at the highest level. The energy consumed from the grid is very low and the battery is more often used to store the over-production than to reduce the consumption during peak hours. As the Smart V2 expert rules consist in discharging the battery during high or medium price, the battery is not used at the maximal capacity. The savings could be increase discharging the battery during the night, when the price is low. Over the year, the Dual strategy is more adapted.

For this district configuration, a solution to have constant savings over the year could be to use wind turbine instead of PV or to use seasonal storage.

Impact of price profile

The objective of this study is to see how the electricity price influences the savings. Three price profiles with different variations are considered. The first and the second profiles have three levels of price: 6 c€/kWh during the night, 12 c€/kWh during the day and 40 c€/kW during peak hours. The peak hours are in the middle of the day for the first profile and in the morning for the second one. The last profile has two levels of price: 7.2 c€/kWh during the night and 8.9 c€/kWh during the day. It corresponds to the Lavrion price profile.

For each profile, the energy cost is summarized in the following table.

	Profile 1	Profile 2	Profile 3
Standard	614 183 €	720 232 €	451 528 €
Smart V1	515 214 €	621 888 €	363 396 €
Smart V2	444 325 €	474 246 €	379 741 €
Dual (with pfct forecast)	386 926 €	385 865 €	344 607 €

In this district configuration, the dual strategy is the most efficient for the cost reduction.

Impact of weather file

The objective of this study is to see the impact of the weather profile. In addition to the Berlin one, those of London, Chambery and Greece are used. For all of them, the load profile has been created using the detailed simulation of the Virtual District. The following table gives the new annual energy consumed by the load and produced by the PV.

	Load consumption	PV production	Ratio
London	6 819 MWh	5 037 MWh	74 %
Berlin	8 662 MWh	5 130 MWh	85 %
Chambery	7 500 MWh	6 353 MWh	136 %
Greece	6 133 MWh	8 328 MWh	59 %

The Berlin climate is relatively cool and this implies a global consumption higher than the others. In Greece, the days of sunshine are longer and more regular throughout the year. The PV production is then more important and even higher than the load consumption.

The electricity price used in the simulation is the one of the first configuration. In this study, only the Standard, Smart V1 and Dual control strategies are tested. The Smart V2 is not used because the expert rules need to be adapted for each weather profile to obtain good performances.

For all the weather profiles, the battery addition considerably reduced the cost (≈ 20%). In the case of Greece, as there is more production than consumption and radiance more distributed during the year, the cost savings is more important in the Smart V1. The cost reduction of the Dual approach for this particular city is reduced. For all the other cities, the dual increase the cost savings of around 25% compared to the Smart V1 approach.

Impact of the renewable energy system

As it is explained in the first results part, the PV is not fully adapted for this kind of load. The consumption is high in winter and low in summer while the PV production is high in summer and low in winter. The usage of a wind turbine instead of a PV helps to have a production more regular throughout the year and then, savings more constant.

The wind turbine is configured to have a maximum produced power of 8.4 MW. The weather and price profiles are the ones used in the first configuration.

The annual wind turbine production is equal to 1,6 MWh. Compared to the load consumption, it is relatively low. The period with over-production is occasional and the usage of the battery without electricity price consideration is limited. The Dual strategy is still the most profitable.

Impact of multiple batteries

The objective of this study is to see how the algorithms manage two different batteries. Both battery sizes are fixed at 2 MWh. The first one has efficiency around 0,8 and the second one around 0,5. Only the Standard, Smart V1 and Dual strategies are considered. In Smart V1, the control strategy manages both batteries in the same way. The set-point is calculated as the sum of the load consumption and the PV production, divided by two. The price and weather profiles are the ones used in the first configuration.

The battery with the efficiency of 0,5 is only charged if the other battery cannot store the over-production (fully charged) and discharged if there is over-production in the next 24 hours. The losses generated by the usage of this battery are too high to use it in others cases. The battery with the high efficiency is used to store the over-production and to optimize the energy cost.

The Dual case has the higher cost savings. It is more generic than the Smart V1 and easiest to implemented, since it optimally adapts to the specific configuration of the district.

Results conclusion

In all the previous studies, the Dual strategy is the most efficient for the cost savings. Globally, the expected AMBASSADOR performances are reached but the savings depend a lot on the conditions (district configuration, climate conditions, etc). In some simple case, the smart algorithms allow having good performances but the expert rules need to be adapted for each new configuration. The Dual approach is more generic and can address more various cases without having to adapt the algorithms. As it is done for the previous studies, the district simulation platform helps to understand and validate the algorithms behaviour but also to run various sensitive simulations.

7. Conclusions

The overall concept, the architecture and objectives described in the very early stages of the project have been implemented on demonstration sites and extensively simulated with the tools developed within the project.

Complex and simplified models have been tested and validated within the District Simulation Platform. Prediction algorithms have been developed in order to enable predictive control of buildings and district. Extensive use has been made of Model Predictive Control, for each system and sub-system of the district.

Demonstration has been done that energy can be optimized in a district, with centralized controllers in the case of private campus, and with distributed optimization in the case of multiple organization district.

Two methods have been tested and compared for distributed optimization: primal and dual decomposition.

Substantial savings have been demonstrated at building and district level. At building level, the implementation of MPC showed savings ranging from 10 to 40% with an average of 28%. For district heating, and in the case of BedZED demonstration site, algorithms developed for existing boilers have demonstrated potential saving of 20% on gas consumption. In the case of multiple organizations district, 10 to 20% of impact on cost has been achieved thanks to smart algorithms.

When moving to implementation on demonstration sites, as expected, communication infrastructure, and equipment controllability was essential. On the very early stages of future projects, it will be important to conduct an audit aiming to identify the flexibilities embedded into existing process, and ensure that those flexibilities can be monitored, characterised and controlled.

Knowledge, results, methods and tools developed within AMBASSADOR will be extensively used in future commercial projects. Simulation tools, and expertise gathered in the frame of AMBASSADOR will be precious assets when addressing new opportunities and evaluating potentials for end users.

The potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results

We foresee different options for business impacts for the concepts and technologies developed within the AMBASSADOR project. Private campus, hybridation market, and smart districts.

As already mentioned earlier, private campus is already an existing market. Especially in the areas where energy supplied by the grid is not secured enough or where environmental hazards such as earthquakes or cyclones are feared. This is typically the case in the US or in Japan, where both drivers apply and communities or private organizations are willing to secure their business. In some places of Europe, we might find some places where main grid topology creates weak areas that will suffer from more power outages than in other regions. In those areas of the world, being able to maximize the use of renewable energy sources when the campus has lost power from the grid is a real challenge. We also see use cases where the ability to limit peak loads to the grid will avoid heavy investments on the power system. Here AMBASSADOR technologies can bring significant contribution. The same technology can also be used in normal operations, in order to optimize the energy bill.

Even though hybridation market is not the preliminary target of the AMBASSADOR project, we foresee commercial opportunities in areas of the world where access to energy is a challenge: Africa, Asia Pacific, India and more specifically, islands. In many cases, energy is supplied by diesel generators with of course the negative impact gensets have on CO_2 emissions. More importantly, for the local communities, logistics costs related to fossil fuel transportation leads to high costs and high dependability to fuel availability. Hybridation of those power plants with renewable energy sources, dispatchable (biomass) or none dispatchable (PV, wind), will relax the pressure of fossil fuels cost and availability. Here again, we see the need to combine flexibility, in the process, or through batteries, with advanced algorithms that will predict the needs, PV and wind production, and adapt flexibilities management consequently. As for private campus, this market already exists and industrials such as Schneider or Leclanché are addressing those needs.

Finally, comes the question of districts and smart cities. Here the situation is much more complex, mainly because of the presence of multiple actors. Still, there might be opportunities in cities for municipalities who own and operate multiple buildings and assets. Here, we are coming back to the concept of the single owner with what can be called a virtual district comprised of municipal buildings spread over the city. Each building will need a local optimization. Global coordination can be considered with the DEMIS in order to limit peak consumption of foster renewable energy penetration.

Things become a real challenge when trying to address multiple actors districts. The opportunities we foresee are pilot projects, where cities or communities concerned about environmental challenge, want to experiment new concepts. Here the question of inhabitant engagement and financial flows remains open. We see many initiatives with technologies such as the block chain, but still demonstration needs to be done that those solutions will be able to scale up efficiently. For now, most of those opportunities are set-up and run as pilot projects, and financial support in required to put in place such initiatives.

The AMBASSADOR project disseminated its results to the European research and industrial community and targeted also all stakeholders of the smart city value and assured an on-going communication between the general public, municipalities, housing associations, architects and engineering consultants, equipment producers etc. on one side and partners of the project on the other. The dissemination strategy was set up in order to plan the best dissemination routes for the AMBASSADOR results (e.g. through project webpage, project dissemination materials, AMBASSADOR summer schools, participating in events, clustering activities etc.).

The AMBASSADOR website (http://www.AMBASSADOR-fp7.eu) has been operational from the end of January 2013. The webpage is considered as a successful tool for raising awareness of the project and its activities. In total the website had more than 17.000 users with their peak around the time of the final conference and AMBASSADOR Innovation Day (September, October 2016). Additionally, a web-based platform for easy and quick access to the power meters readings of the LTCP buildings was created. Among the other uses of this web tool (evaluation of the DSP platform etc.) it was also a very useful dissemination tool that was included to the AMBASSADOR web page. The visitors of the AMBASSADOR page were able to roll over a building and were able to see information regarding each building such as: building characteristics, real time readings of power/energy consumption, RES production as well as hydrogen storage.

AMBASSADOR homepage with the invitation to the final conference and Innovation Day

During the project, **several dissemination materials** were developed including the project leaflet, project roll-up as well as AMBASSADOR video and teaser. The first AMBASSADOR video was released summarizing the project objectives, presenting the project test sites, stressing the main technical progress done during the first year. Further on a synthetic video (AMBASSADOR teaser) about 3minutes long has been prepared to explain the AMBASSADOR project to anyone, in the context of smart cities and smart districts, what is the technology used and why it is advantageous and different from other "smart" projects. Both the video and teaser are available on the AMBASSADOR website.

AMBASSADOR dissemination materials

AMBASSADOR also contributed to several editions of EeB project review. The aim of the publication is to provide a dissemination route for EeB PPP projects; capture and showcase the impact of EeB PPP projects; cluster projects by topics to demonstrate continuity of activity; demonstrate the wave-based activity facilitated by the EeB PPP; constitute an effective set of case studies that will encourage further companies to join the association and participate on future EeB PPP calls.

AMBASSADOR press release was prepared at the end of the project and shared through partners' networks. Objective of this press release was to announce the end of the project, to highlight the main achievements and perspectives for future exploitation. In the relation with the AMBASSADOR final conference, the Technical

Chamber of Greece as well as numerous national newspapers having the highest reading rates, presented articles dedicated to the AMBASSADOR project's scopes and targets.

Clustering activities were planned as a necessary part of the project dissemination. AMBASSADOR project participated in several editions of Workshop on the Impact of EeB PPP that was jointly organized by the European Commission with the support of the E2BA. The objectives of the workshops were to address innovation and exploitation issues in running projects and explore potential for cross-project clustering. Several joint workshops were also organised in cooperation with the RESILIENT project The main goal of these meetings was to discuss and understand the positioning of the two projects towards each other (since they have been both funded from the same call topic), to identify common actions and share ideas on possible cooperation. Key common areas of interest were identified, action list proposed and further cooperation between the projects had been foreseen. Common areas of interest were identified as optimization, district models and dissemination. AMBASSADOR had also very strong synergies EUREF / InnoGrid project. As a joint venture has been launched between InnoZ and Schneider Electric, closer collaboration between the two projects started. The areas for collaboration were focused on the DSP; later on the cooperation on algorithms is expected. DSP was transferred to InnoGRID and valuable feedback from InnoGRID was shared with the AMBASSADOR team.

Publication of AMBASSADOR results to relevant scientific and industrial periodicals, journals and key conferences in Europe was assured during the whole project lifetime. The project participated with a project booth in conferences such as Industrial Technologies 2014 (April 2014, Athens) or Re-Industrialisation of Europe 2016 (October 2016, Bratislava) with also oral contribution from the project coordinator. Project results were also presented at several editions of Sustainable Places conference (2013, 2014, 2015), where also joint workshops on topics such as business models were organised with related projects in EeB domain. Furthermore, the project was represented at Energy Efficiency Conference 2013 (Athens, March 2013), Semanco workshop (Barcelona, April 2013), Greek Innovation Expo 2013 (Athens, May 2013), SmartinMED workshop (Milan, March 2014), IEC board – AMBASSADOR presentation (Rueil, June 2014), Construction and Built Environment – Future Horizons (Brussels, June 2014), IEA EBC Annex 60 second expert meeting (Lund, September 2014), Journée Microgrids (Lyon, October 2014), IEEE SmartGridComm (Venice, November 2014), EinB2014 - 3rd International Conference ENERGY in BUILDINGS 2014 (Athens, November 2014), Smart City Expo (Barcelona, November 2014), PowerTech 2015 conference (Eindhoven, June 2015), CISBAT 2015 (Lausanne, September 2015), 11th International Modelica Conference 2015 (Versailles, September 2015), EMENDER 2015 (Ljubljana, October 2015), 14th International Conference of the International Building Performance Simulation Association (IBPSA), (Hyderabad, December 2015), ENERGYCON 2016 (Leuven, April 2016), Explore Innovation, Schneider Electric (Athens, June 2016), IAHS 2016 (Algarve, September 2016), 11th SDEWES conference (Lisbon, September 2016). Peer reviewed articles were prepared for SDEWES 2016 conference as well as IAHS World Congress 2016 and are available in their proceedings. AMBASSADOR project was also presented in the VTT Research Highlights publication.

AMBASSADOR results were also dissemination through **AMBASSADOR training for energy managers** that took place in November 2014 in Chambéry at CEA-INES test site. The training was dedicated to topics such as overall energy context, optimization strategies for buildings and districts dimension. The practical demonstration of the District Energy Management and Information System (DEMIS) was also performed. As a follow-up to this training, **AMBASSADOR Innovation Day** was organised in October 2016. It was again hold at CEA-INES demonstration site in Chambéry and as the public was French, it was decided to have all the presentations in French. Among the participants, there were representatives from SIG Genève, Tenerrdis, CSTB, Planair or Schneider Strategy.

At the end of the project the **AMBASSADOR final conference** took place (Lavrion, October 2016). During the event the project was revealed to the public and the results were made well known to the audience. This was a very important action for the recognition of the project to the public and for giving the importance of project's targets regarding the sustainable energy management in district community level through the contribution of buildings' automation and algorithms implementation for managing the energy mix. The representatives from the whole project's consortium were giving all the necessary information and gladly answering all the questions given from the public. The conference attracted a wide range of stakeholders from the whole value chain, such as representatives from the industrial sector and the public authorities, engineers from different field as well as students and private investors. Additionally, national media, having high broadcasted rates, covered the final conference of the AMBASADOR project and make it well known to the national audience. On 12/10/15 Skai TV, one of the largest media groups in Greece broadcasted in national level during the breaking news a documentary presenting AMBASSADOR scope and the final conference results. On 15/10/16 broadcasted a more detailed documentary including a live interview with NTUA researcher.

During the whole course of the project, a large number of visits from different educational levels (schools, universities, institutions, etc.) were organised at the Lavrion test site with the goal to continuously inform and disseminate the research activity in LTCP in a wide-range audience from students to engineers.

AMBASSADOR final conference

AMBASSADOR test site visits

AMBASSADOR exploitation activities were designed in order to evaluate the collective impact potential of the consortium by evaluating the market potential and to determine product opportunities in relation to the customer/product requirements throughout the course of the project. The activities covered the methodology developed by the consortium to complete a market description of districts, to identify the different actors of the added value chains and their behaviours and expectations in the field of value of AMBASSADOR. The exploitation plan was focused on three business cases for buildings (Single owner private campus, Single owner building stock called virtual campus and Single owner utility network, utility being understood as the addition of an energy provider and DSO) and districts (Single owner private campus, Single owner building stock called virtual campus and Single owner utility network, utility being understood as the addition of an energy provider and DSO) and two use cases (Energy bill optimisation including: tariff optimisation, CO_2 emission valorisation, ancillary services evaluation and District resiliency including: outages mitigation; energy unit commitment and connection and disconnection from the main grid in the case of microgrids). For buildings only one stakeholder was considered whatever the business case and that was the energy manager responsible for the energy bill optimisation and for districts two different stakeholders were considered whatever the business cases is and these were the energy manager responsible for the energy operation and the network owner responsible for the capex planning. The possible business model depend on the money flows on the district, but for the Enernet situation (sharing economy), further works would be required in order to understand money flows.

Exploitation of AMBASSADOR results has been an important objective for most of the partners. Few examples can be shared here, demonstrating how AMBASSADOR concept or components developed within the project contribute to new opportunities.

Learning Grid by Grenoble

Grenoble Chamber of Commerce and Schneider Electric have setup together a project that is the first European private campus combining smart campus and education. This campus, comprised of 6 buildings is energized both by electricity and city heating. The objectives are to contribute to young populations training to novel energy management solutions, and in terms of environmental objectives, to foster renewable energy sources penetration while maximizing self-consumption.

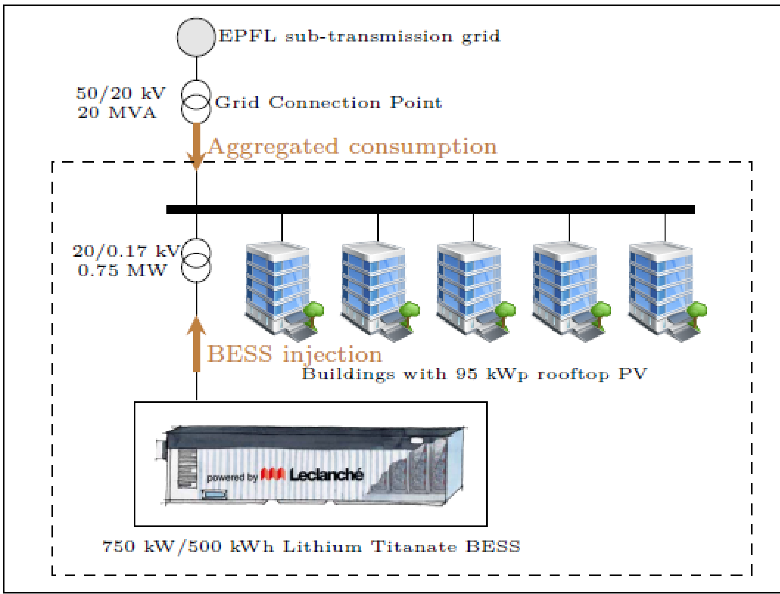
For the purpose of this project, PV, batteries, EV charging stations, a CHP and heat storage will be installed. On top of those equipment, existing Schneider Electric offer for energy management will be upgraded, benefiting from the very last developments of AMBASSADOR project. In particular, a DEMIS will be deployed, allowing optimal coordination of existing buildings.

To learn more: http://www.imt-grenoble.fr/le-learninggrid-by-grenoble-est-lance--41845.kjsp?RH=Agenda_IMT

EPFL campus Lausanne

Leclanché installed a battery in EPFL campus. The utility-scale battery energy storage system is coupled with prosumers (office buildings equipped with rooftop PV), of which the total presumption is monitored. The BESS active power injection is controlled such that the composite consumption (prosumers + BESS) follows a scheduled profile, said dispatch plan, established on a day-ahead basis. This is with the objective of achieving dispatched-by-design operation, thus reducing the amount of regulating power required for grid operation. The dispatch plan can be also built to satisfy a certain objective for the local utility company, for example to perform:

- peak shaving/congestion management/load leveling;
- minimization of the cost of the imported electricity;
- maximization of self-consumption of locally generated electricity.



To learn more: http://actu.epfl.ch/news/leclanche-and-epfl-innovate-to-store-solar-energy/

Zero carbon housing Developments (in Planning)

BedZED has a zero carbon housing site under development is the UK which offsets all the energy bills of the 96 zero carbon homes by using a combination of PV, self consumed battery storage, Feed In Tariff income, export to the grid. Each home will be equipped with 7.5 kWp of PV and 7.5 kWh LiPo batteries, with the objective of self consuming 80% of the time. In order to inject solar generation into the grid, an additional battery will be installed at district level, storing energy from peak production, and shedding peak demand.

To learn more: http://www.zedfactory.com/newport

The address of the project public website, if applicable as well as relevant contact details

Webpage

- http://ambassador-fp7.eu/

Project coordinator

- Mr. Alfredo Samperio (Schneider Electric Industries SAS)
- E-mail: alfredo.samperio@schneider-electric.com
- Tel: +33 (0) 476 39 82 88

Project manager / Dissemination manager

- Dr. Václav Smítka (Amires s.r.o.)
- E-mail: smitka@amires.eu
- Tel: +420 732 304 379

Exploitation manager

- Mr. Olivier Cottet (Schneider Electric Industries SAS)
- E-mail: olivier.cottet@schneider-electric.com
- Tel: +33 (0) 476 39 11 48

List of partners

Schneider Electric is the global specialist in energy management and automation. With revenues of ~€27 billion in FY2015, our 160,000+ employees serve customers in over 100 countries, helping them to manage their energy and process in ways that are safe, reliable, efficient and sustainable. From the simplest of switches to complex operational systems, our technology, software and services improve the way our customers manage and automate their operations. Our connected technologies reshape industries, transform cities and enrich lives. At Schneider Electric, we call this Life Is On. For more information: http://www.schneider-electric.com/

CSEM (Swiss Centre for Electronics and Microtechnology), founded in 1984, is a private research and development centre, which has specialized in microtechnology, nanotechnology, microelectronics, systems engineering and communications technologies. It offers its customers and industry partners tailor made innovative solutions based on its technological expertise from applied research. Furthermore, in founding start-ups, it actively contributes to developing Switzerland as an industrial location. For more information: http://www.csem.ch

CEA (Commissariat a l'Energie Atomique et aux Energie Alternatives) is involved in AMBASSADOR through its Technological Research Division. Part of this division, the CEA LITEN (Laboratory of Innovation for New Energy Technologies and Nanomaterials) is a CEA department located for the most part in Grenoble and Chambéry (on the INES site – French National Institute for Solar Energy). It is one of Europe's newest and most important research centers in the new energy technology field. Involved in 350 research partnership contracts every year, LITEN works hand in hand with French industry. It is one of the CEA laboratories with the most patents – 230 new applications filed per year and a portfolio of 1 200 international patents. LITEN's research activities are focused on solar energy, low-energy buildings, future transport applications (hydrogen, fuel cells and batteries), as well as nanomaterials for energy and methods guaranteeing their safe use. For more information: http://www.cea.fr

Neurobat AG develops innovative products and cutting-edge technologies for the optimization of heating systems. Its product portfolio ranges from simple add-on equipment for heating installations in single-family houses to integrated-chip solutions for heating appliance manufacturers and online energy optimization systems for commercial properties. Its clientele includes single-family home owners as well as heating appliance manufacturers (OEMs), property and facility management companies, and big-name Swiss corporations. The products of this Swiss high-tech company excel by exceptionally high energy savings of up to 28%, supreme indoor comfort, low maintenance and straightforward application. The company, which was set up in 2009, having won a string of awards for its trailblazing technology. For more information: http://www.neurobat.net

Leclanché is a fully vertically integrated battery energy storage solution provider. It delivers a wide range of turnkey energy storage solutions for homes, small offices, large industries, electricity grids, as well as hybridization for mass transport systems such as bus fleets and ferries. Established in 1909, Leclanché has been a reliable partner for battery energy storage solutions for over 100 years. Founded in the tradition of Georges Leclanché, the inventor of the dry cell battery, Leclanché today has a rich portfolio of Battery Energy Storage Systems (BESS) that include bespoke battery systems from industry leading lithium-ion solutions. For more information: http://www.leclanche.com/

IK4-TEKNIKER is a technological centre legally, constituted as a private not-for-profit Foundation in 1981, that currently counts with a staff of 270 professionals and a turnover of about 23 M€ in 2015. Its mission is to help the industrial sector to increase its innovative capacity by means of generating and applying technology and knowledge in order to be more competitive. IK4 TEKNIKER expertise covers a wide range of technologies allowing to provide services to many sectors (energy, machine-tool and accessories, automotive, aeronautics and other space applications, petrochemicals, assistive technologies, among others) and to develop a good variety of products. In line with its missions and origins, IK4-TEKNIKER not only provides companies with technological support, but is also involved in generating new business initiatives. For more information: http://www.tekniker.es/en

Zigor R&D provides adapted and technologically advanced solutions for the energy conversion needs of companies belonging to the fields of telecommunications, industry, railway, renewable energies and energy, utilities and municipalities. ZIGOR is a company engaged in the design, manufacture and marketing of a wide range of DC/AC Power Conversion Systems and the development of customized electronic solutions, e.g.: battery chargers, battery chargers high frequency switching mode technology, battery chargers for lmds, telecom battery charger, DC/DC converters, Inverters, Uninterruptible Power Systems (UPS) and electronic voltage regulators, PV solar and wind power inverters, energy saving equipment (for peak saving) and Lighting energy saving equipment.For more information: http://www.zigor.com

D'Appolonia S.p.A. is a major Italian firm which provides integrated engineering services to clients belonging both to the public and the private sector in the energy, environment, construction, oil and gas, transport, electronics and telecommunications domains. To offer high level services worldwide, D'Appolonia relies on a permanent staff of qualified engineers and scientists. Most of the staff has an extended academic and technical background with post-graduate degrees. In the field of Energy Efficient and Green Buildings, the multidisciplinary staff of D'Appolonia guarantees deep knowledge in materials engineering, advanced insulation systems, their assembly installation, and maintenance. For more information: http://www.dappolonia.it/

NTUA (National Technical University of Athens) is the oldest and most prestigious technical university in Greece with 9 schools and more than 7000 students. Today NTUA employs 1900 persons as academic or administrative staff and more than 2500 researchers. Based on the 2011 Euro Research Ranking Data, NTUA is positioned in the 10th place between educational organisations and in the 9th position on Networking Rank (Reputation). Last year only, it was coordinating or participating in 67 European projects and during the last decade was funded from European Commission 400M€. Based on the same statistical data, the Laboratory of Metallurgy (NTUA.LM) is ranking in the 1st position between NTUA Laboratories. For more information: http://www.ntua.gr/index_en.html

Planair SA is a Swiss SME established in 1985. The company employs 40 engineers and technicians, active in the field of energetic and environmental consultancy in building and renewables domains, gathering knowledge and competencies both in technical domains (HVAC) and in R&D projects. The company is active in energy planning and efficiency at district/regional level, as well as energy saving programs. Planair has several collaborators who are IPMVP certified. For more information: http://www.planair.ch/en/welcome/

ECBrussels participated in several projects providing direct technical consulting on the European and national legislations in the renewable energy field. Within the OILECO project, co-financed by the European Commission through the Intelligent Energy for Europe Programme, its role is to provide technical information regarding the legal and administrative background in the field of re-use of Used Cooking Oils to produce bio-fuel. Moreover, ECBrussels designed and delivered the Analysis of European Energy Market and

Policies, built on the legislative monitoring of the energy sector, the creation of reports on energy trends, studies on EU legislation on energy, analysis of the market evolution. For more information: http://www.ecbrussels.com/

VTT Technical Research Centre of Finland Ltd is a state owned non-profit limited liability company established by law and operating under the ownership steering of the Finnish Ministry of Employment and the Economy. VTT's activities are focused on three areas: Knowledge intensive products and services, Smart industry and energy systems, and Solutions for natural resources and environment. VTT is impact-driven and from its wide multi-technological knowledge base, VTT can combine different technologies, produce information, upgrade technology knowledge, and create business. More information: http://www.vttresearch.com

ZEDfactory was founded in 1999. The company aims to demonstrate that a step change reduction in carbon footprint is achievable at the same time as an increase in overall quality of life – with a zero carbon, zero waste lifestyle, and work style achieved by synchronising urban ZEDs with zero fossil energy farming and food distribution. ZEDfactory has developed its own building physics models tuneable to different climatic regions, has its own 'ZEDfabric' low cost bulk purchasing supply chain with specially developed energy efficient and building integrated renewable energy systems. For more information: http://www.zedfactory.com/

AMIRES is a consulting and management company for research, development and innovation projects, which provides the necessary strategic and administrative support to high quality international teams to achieve their objectives and facilitates the research-industrial and research-policy making interface. AMIRES follows projects from their initiation and planning, through negotiation, execution and management to the final stage, where exploitation of a new technologies, products or services is facilitated. Moreover, main mission of the company is to facilitate the access of European research to high-tech SMEs and improve exploitation of innovative ideas. For more information: http://www.amires.eu