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ComBioTES
Compact bio-based thermal energy storage for buildings

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= Deliverable D4.1=

Modular-based design of the EMS: architecture and Requirements

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Executive Summary

The ComBioTES project proposes to develop a modular compact Thermal Energy Storage (TES) solution for both heating, hot tap water and cooling with regard to thermal end-uses in buildings. On one hand, ComBioTES concept proposes to design a switchable water TES to store hot tap water and can also be converted into ice storage during summer for cooling needs. One the other hand, a compact Latent TES (LTES), using high performances bio-based PCM, to store high heating energy amount, usable either for space heating, or for hot tap water demands, will be developed.

The objective of WP4 is to develop a modular-based intelligent optimal energy management system (EMS) algorithm based on a data-driven approach, with each module carries out certain functions, e.g., control, communication, data management, modelling, forecast and optimal decision-making. The developed algorithm will optimally manage and control the energy flows (i.e. heat and electricity) of the compact thermal energy storage developed by WP2 in order to meet a number of operational objectives simultaneously, e.g. meeting end users‘ comfort requirement, operating the system at minimum cost and using its flexible storage capacity to provide various electricity grid operation needs like peak load reduction, reducing renewable energy curtailment and grid balancing.

This deliverable contains explanation and requirements of the EMS architecture, each module and specification of modular interfaces, in order to guide the EMS development and implementation. An MPC-based control architecture is also presented, as an illustration of the minimum requirement. Since sufficiently inputs from WP1 are not yet available, this deliverable mainly focuses on the description of the methodology, the different technical choices that can be made regarding the objectives and the available inputs, the consequences of these choices etc.

Practice and detailed implementation of this methodology will be part of deliverable D1.3, once detailed information of the use-cases is known.

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1. Introduction and context

The energy management system (EMS) developed in ComBioTES aims to achieve a techno-economic optimal operation of the electrical thermal energy storage unit (ETES) by calculating and dispatching control signals or operation plans continuously in real-time. ComBioTES has the aim of developing and demonstrating an electric thermal energy storage system (ETESS) solution, i.e., the combined EMS and ETES, in households in different countries where the operation needs, objectives and environment may vary significantly.

To achieve a generic solution, we will use modular design of the EMS and its strategy due to its advantages in flexible development, easy maintenance and high adaptability as "plug and play". Each module within the EMS will carry out certain functions as illustrated in Figure 1, e.g., system configuration, interface and data management, modelling, forecast and optimal decision-making, etc., and can have various ways of implementation. Coupling these modules will give shape to a specific structure, such as a model-predictive control (MPC) program, for fulfilling various operation needs of different demo sites involved in ComBioTES.

This document will contain explanation and requirements of the EMS architecture, each module and specification of modular interfaces, in order to guide the EMS development and implementation. An MPC-based control architecture is also presented, as an illustration of the minimum requirement.

2. Architecture

2.1. General overview

The proposed EMS, as depicted in Figure 1, deployed as a service layer that interacts with the physical layer and the information layer.

At the physical layer, the ETES unit will be the main physical unit that will be controlled/dispatched by the EMS system. The ETES unit should have its own process control (such as implemented by PLC) in order to execute the received control/dispatch signals. To achieve a closed loop control, the ETES should also report its performance variables (e.g., state of charge, measured temperatures and flow rate, status of valves, etc.) to the EMS through the information layer.

Through the information layer, the EMS will communicate with but not limited to the following stakeholders (and their systems) in order to meet the operation requirements of the ETESS in different demo sites:

- the end user who may provide direct request of energy demand and settings (e.g., on/off), or an indirect request of energy demand by pre-setting a temperature target of space heating (SH)/domestic hot water (DHW) in order to meet objectives, e.g., an acceptable comfort level and/or energy cost saving;
- the aggregator/energy supplier who may want to control the ETES directly (such as by sending one or a series of energy/power request) or indirectly (such as by sending energy prices or energy consumption limits) in order to meet objectives, e.g., portfolio optimization and/or energy efficiency etc.;
- the grid operator who may want to control the ETES directly (such as by sending one or a series of energy/power request) or indirectly (such as by sending prices/premiums of different types of grid services in order to incentivize the end users' participation in demand response programs) in order to use the flexibility offered by the ETESS to support grid operation;
- Others, such as building/smart home operators who may want to integrate the ETESS into their portfolio or just provide additional information, such as weather forecast, building demand estimation, household energy infrastructure models, parameters, and live measurement of other household energy units (such as PV, battery).

The EMS, as a modular-based service platform, will be able to host a number of functional modules through a Runtime Environment (RE), which are explained in the following section.

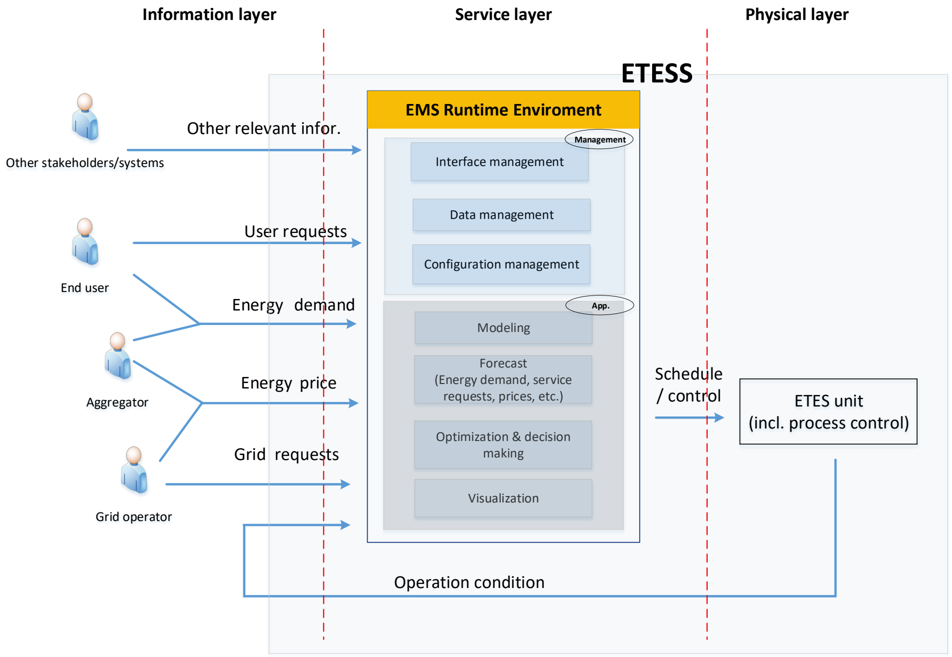

Figure 1: A schematic diagram of the ComBioTES EMS architecture.

2.2. Modular functions/applications of the EMS

EMS Runtime Environment: An EMS RE refers to all the resources needed to support running the program. This includes backend libraries, processes, virtual machines, etc. which all together allows the EMS program to function in an Edge device, such as a Raspberry Pi, Arduino IoT (with GNU/Linux/Windows Operating System) or a cloud. The selected RE shall be able to support the development, implementation and execution of relevant EMS functions using high-level programming language, such as Python, Java, C++, or MATLAB etc. The general operation principle of the EMS follows a classical IPO (input-process-output) model, as in Figure 2, which defines the execution cycle corresponding to Figure 1.

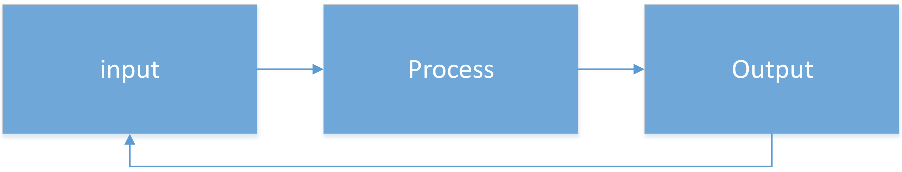

Figure 2: An input-process-output model in software engineering.

Basic Modules: the EMS needs to have a series of basic functions, such as archiving, reporting, messaging, logging, calculation, based on which advanced EMS applications can be executed. Among these modules, three main modules are identified and explained below (also due to the fact some of the basic functions might be provided by the RE library).

- **Interface management:** this module establishes and maintains relevant cross-layer and cross-module information exchange during the entire process of EMS execution. Ideally, the EMS shall be developed according to standard demand response (DR) protocols using common information models (CIM) or Unified modelling language (UML);
- **Data management**: through the interface module, the data management module deals with collection (via MODBUS TCP/IP or as a CSV file via FTPS), organization, protection, and storage (via a database) of different types of data, such as measured/received inputs, calculated outputs and intermediate results, etc.;
- **Configuration management**: is the module that allows for configuring the EMS w.r.t each module setting, if relevant.

Advanced Modules: built on top of the basic module, advanced modules provide the EMS with a set of powerful functional applications that deliver an MPC-based optimal energy management solutions to one or more stakeholders through controlling and/or scheduling the physical ETES in real-time. These functions may involve

- **Modeling:** As cost-efficiency of an ETES model is dependent on its application which may vary from one demo site to another in the ComBioTES project. This module could contain real-time control-oriented models of ETES (w.r.t configurations and granularity) that are derived using different methods, e.g. white-box, grey-box and black-box, in order to enable adaptive selection.
- **Forecast:** This module delivers short-term forecast (1 min– 1 hour– 1day– 1 week) of related techno-economic features, e.g., weather, energy price, energy demand etc. Different techniques, e.g., statistical, machine learning (ML), physical/numerical, and hybrid may be applied. It is also possible that there are service providers who could provide high-quality forecast services to the EMS though the basic modules.
- **Optimization and decision-making:** Together with the two other advanced modules, i.e., modeling and forecast, the three advanced modules, when they are seamless designed and integrated, deliver a full-scale MPC program. This module thus is the core module that computes optimal manipulated control setpoints by solving a formulated optimization problem at each decision interval. Optimization packages/services often need to be pre-installed in the RE and be called by the decision-making module. As the ETES applications deployed in different places could have different operation objectives, such as cost-minimization, meeting comfort expectations, providing grid services etc., the optimization needs could be envisioned as a multi-objective problem, wherein each sub-objective is assigned a weight coefficient.

- **Visualization:** This module provides various types of diagrams and representations for visualizing the data needed for various purposes, e.g., illustration and evaluation the implemented control strategies.

Today, there exists multiple commercial or research-oriented EMS applications and frameworks, such as ISO 50001 (https://www.iso.org/iso-50001-energy-management.html), Spring and Spring Boot [1] etc., which have been applied to facilitate EMS design and development. Concerning the needs of ComBioTES, i.e., to develop and demonstrate a cost-effective ETES in Europe and China, when designing and developing the EMS solution, it is necessary to identify requirement attributes, as in Table 1, for each module and its features such as communication frequency and storage capacity. These considerations need to align with the use cases developed in WP1 and the demo plans.

Table 1: Requirements attributes.

Priority	**Semantics**
Must have	Mandatory requirements that are fundamental to the EMS/module
Should have	Important requirements that may be omitted
Could have	Requirements that are truly optional
Want to have	Requirements that can wait for later releases

3. MPC– EMS strategy with minimum requirements

For ComBIOTES, the EMS can have various levels of capability, such as from managing a single ETES to managing an ETES together with the associated household energy assets (such as a heat pump) or even could be perceived as a platform for managing multiple ETES units that are deployed in different demo sites. Considering its minimum requirement, i.e., to achieve an optimal control of the controllable assets under different operation environments and objectives. In this section, the control architecture and principle of different MPC setups are introduced. The decision of the selected MPC implementation, again, is dependent on the application needs and selection of hardware and software, w.r.t. online/offline computing power, information storage capacity, communication setup, etc.

3.1. Classical MPC

A classical MPC program, as show in Figure 3, refers to a set of control algorithms that optimize a sequence of adjustments for manipulated variable to keep the reference trajectory over a future time horizon [2]. A process model is applied to forecast the process behaviour in the same time horizon, based on a linear or quadratic objective function, which is subject to equality or inequality constraints.

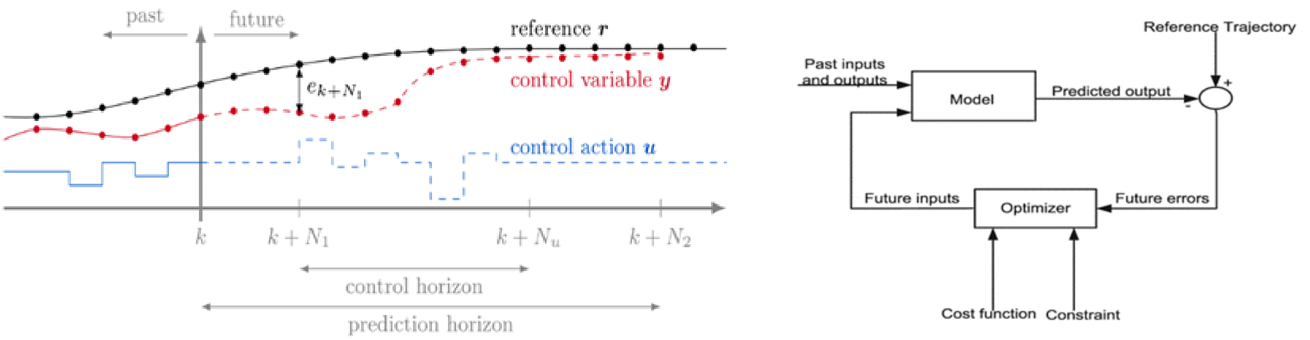

Figure 3: Fundamental principle of a traditional MPC.

In MPC, the optimization is performed repeatedly on-line. Often, the cost function is formulated in such a way that the system output tracks a given reference r for a horizon N_2. The prediction horizon N_2 must be long enough to represent the effect of a change in the manipulated variable u on the control variable y. Delays can be considered by the lower prediction horizon N_1 or by incorporating them into the system model. The receding horizon optimization can effectively incorporate the uncertainties incurred by model-plant mismatch, time-varying behaviour and disturbances [3].

MPC is a recognized powerful approach with well-established theoretical foundations and proven capability to handle a large number of industrial control problems [4]. Due to its ability of incorporating forecast and uncertainty handling into the control, MPC has been largely used in DR applications [5], ranging from a single unit to an integrated energy system, and demonstrated capable of achieving substantial energy savings in dynamic building environment, as compared to conventional control solutions, such as PID [6].

3.2. A Data-driven MPC using both online and offline data

However, the traditional MPC still faces technical challenges like having high quality of forecast and state estimate, needs of high-fidelity models, demand of sophisticated optimization tools/libraries to solve the optimization problem, etc. One possible solution to overcome these challenges is to use data-driven methods, such as artificial neural network (ANN), which needs less effort in model construction and can approximate control laws between model inputs and outputs. In Figure 4, the principle and architecture of a data driven MPC is presented.

Compared to the general architecture of EMS, the data driven MPC architecture can have less requirement on related software platform and framework. Instead, it focuses on delivering a high-quality control service to the ETES and its associated energy systems. Historical data and relevant technical parameters of the ETES and the involved energy system could be provided offline to support the development/training of initial ETES and controller models. When the controller is deployed for operation, real time data could be measured to evaluate the control performance and to update the related models. This learning process enables online adaptation of the developed controller to each demo site. Correspondingly, it requires online data storage and management.

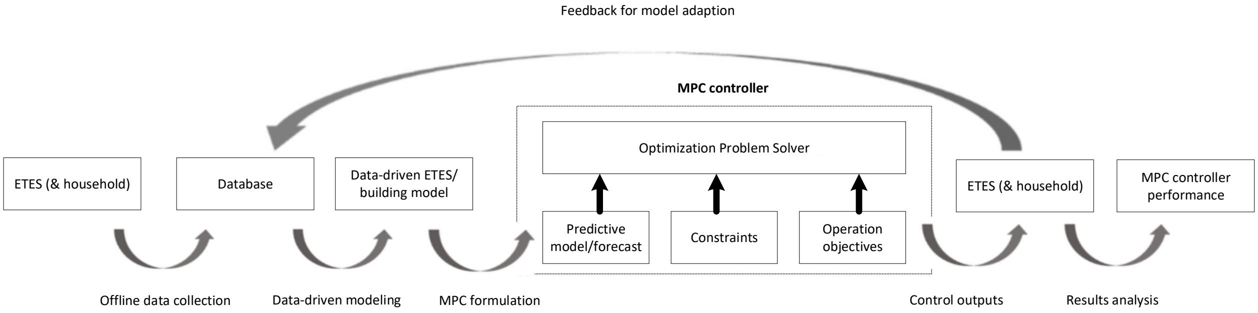

Figure 4: A data driven MPC.

3.3. A Data-driven MPC using offline data

As an alternative to the data driven MPC using online data, it is also possible to use pure offline data, such as data derived from simulation models. This approach does not require any online learning, so the demand of online-communication and online data storage is significantly reduced. However, to reach high quality of controller performance, it requires significant amount of up-front work, such as developing high quality simulation models.

3.4. Computational effort and implementation

The computational effort required by an MPC is dependent on a number of factors, such as sample time, prediction horizon, model complexity (such as linear vs. nonlinear) etc.
Table 2 presents the computational time with varying prediction horizon of a MPC program deployed for an industrial heat booster substation (HBS) [7]. Such a HBS includes one large and one small heat pump, thermal energy storage and a heat exchanger. The MPC was developed to enable ultra-low temperature district heating, economic load shifting and strategic scheduling with time-varying electricity prices. A feedback loop connects the MPC controller to the HBS. At midnight, the MPC fetches the current state values of the HBS and calculates a 24-h heat demand forecast. The controller then initiates a feedback loop with 30-min intervals over the course of the day. All models are based on the detailed and non-linear dynamic models.

The computing effort test was carried out on a laptop with an Intel(R) Core (TM) i7-8550U quad-core CPU @ 1.80 GHz, 8 GB RAM laptop running YALMIP/GUROBI in Matlab2019b, on average the computational time grows exponentially as a function of prediction horizon.

Table 2: Computational time with varying prediction horizon.

Prediction Horizon [hr]	Computational Time [s]
1	13
2	16
3	17
4	20
5	27
6	35
7	68
8	156
9	707
10	679

The above example demonstrated the needs of computational effort estimation for MPC implementation. In general, MPC developed for DR can also classified into the following setups.

- Using a microcontroller (with a microprocessor, RAM, ROM, IO, busses, power management) to implement MPC programs that have little demand for computing power;
- Using a microPC (with a full-fledged Operating System but limited computing power) to implement MPC programs that have some demand for computing power;
- Using a desktop/laptop PC to implement MPC programs that have moderate-high demand for computing power;
- Using server-based solutions (such as high-performance computing) to implement MPC programs that have high-very high demand for computing power.

For ComBioTES, considering that the specific implementation requirements of the MPC program at each demo site at this stage still requires further development and clarification, an implementation as in Figure 5 can be considered to meet the minimum control requirements. This allows for parallel development and update of the MPC and the ETES related local automation solution during the project.

Performance of the MPC can be measured against but not limited to the following indicators

- Energy cost and/or savings;
- Quality of service according to end users' comfort and/or relevant regulatory standards, such as for spacing heating, domestic hot water, and electricity grid services.

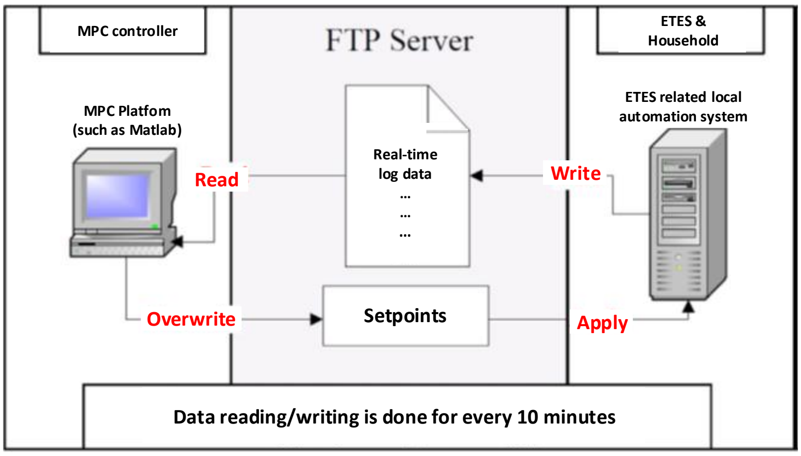

Figure 5: An initial implementation of the ComBioTES MPC.

4. Conclusions

The benefits of modular design include scalability and standardization. Both the EMS and the control strategies can be designed and implemented according to the modular design principle; therefore enabling easy and flexible module creation, modification and immigration.

The practical developments and implementation of the EMS have not been presented in this deliverable, since mandatory information concerning the thermal storage components and the demo-site are still incompletely known.

Concerning the next step, a clear scope and requirements of each demo site within ComBioTES is needed in order to achieve an optimal trade-off among cost, performance and expectations.

A more detailed, complete and demo-site specific definition of the EMS will be presented in deliverable D1.3.

5. Degree of progress

The degree of progress for this deliverable is 100%.

6. Dissemination level

This Deliverable is public and will be therefore available for downloading on the project’s website and on demand.

7. References

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