PRINCIPAL ACADEMIC TUTOR
Sonia Leva, DENG, Politecnico di Milano

ACADEMIC TUTORS
Paolo Lazzeroni, DENERG, Politecnico di Torino

EXTERNAL INSTITUTION
Free2Move eSolutions

EXTERNAL TUTORS
Vinicio Lupo, Free2Move eSolutions

TEAM MEMBERS

Andrea Cuccovillo
Industrial Production and Technological Innovation Engineering,
Politecnico di Torino

Gianluca Giacomelli
Automation and Control Engineering,
Politecnico di Milano

Chiara Magri
Computer Science and Engineering,
Politecnico di Milano

Gianluca Piccoli
Automation and Control Engineering,
Politecnico di Milano

Matteo Pierini
Automation and Control Engineering,
Politecnico di Milano

Martina Tosarello
Architecture for Sustainability,
Politecnico di Torino

eHome Solutions

Smart ecosystems for home charging

Executive Summary

The constantly increasing energy cost and the highly restrictive environmental laws imposed by governments can be seen as a challenge for individuals, but also as an opportunity for companies to leverage the people's need to both save money and reduce their environmental impact. In this context, Home Energy Management System (HEMS) devices are spreading to fulfil such requirements.

A HEMS is a device that allows monitoring the domestic energy production and usage to automatically manage the flows, bringing users to cut energy bills and reduce their emissions. Such achievements can be reached thanks to the integration of different elements that make up the energy network of houses, which can be electric vehicles (EV), smart appliances, photovoltaic systems (PV), energy storage systems (ESS), heating, ventilation and air conditioning systems (HVAC).

As of today, there is currently no "comprehensive" HEMS offered by any provider, as the existing ones can integrate only a small range of smart appliances and do not properly exploit the energetic contribution of critical elements such as EV, PV and ESS.

The goal of this project is therefore to develop a comprehensive HEMS, including a control algorithm and a user interface, able to operate with a broad range of devices and achieve previously unattainable performance.

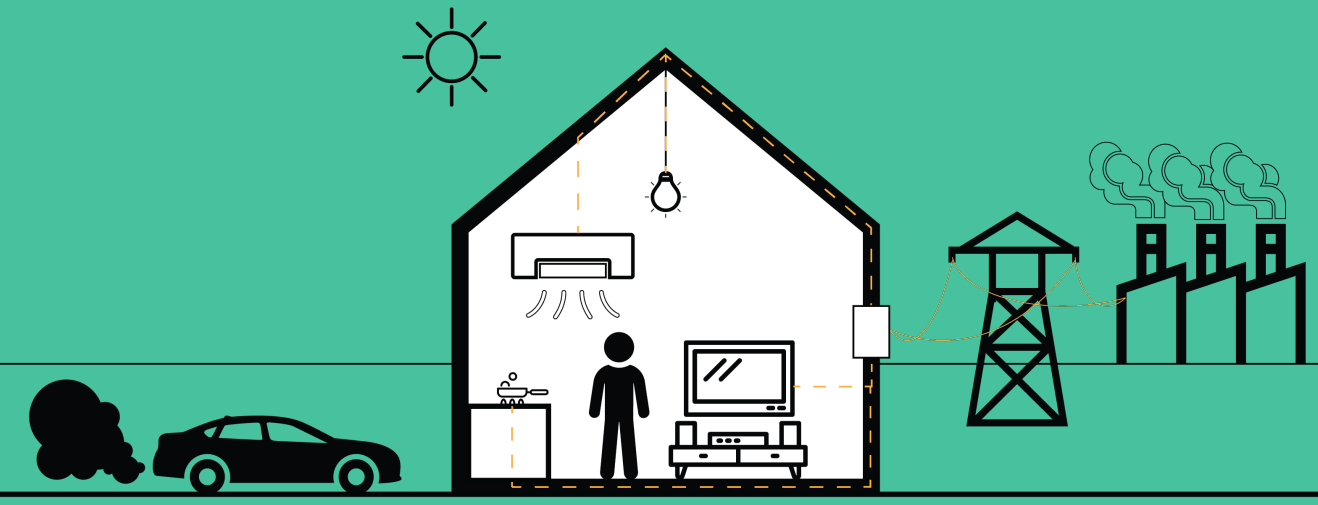
The main stakeholder is Free2move eSolutions, a company active in the field of electric mobility and EV infrastructures.

Key Words

Home Energy Management Systems
Smart home
Energy
Optimization algorithms
User interface
Home devices integration

Without HEMS

- Intelligent energy purchases
- Energy flows management
- Optimal consumption of energy stored



With HEMS

- Energy bills cut
- Reduced CO_2 emission
- House self sufficiency

Project description written by the Principal Academic Tutor

The eHome Solution project focuses on the development of a Home Energy Management System (HEMS), a device for the monitoring and optimal management of energy flows in a house, in order to minimize energy costs. The scenario studied involves a detached house endowed with a bidirectional connection to the grid, photovoltaic (PV) panels, a stationary battery and an Electric Vehicle (EV) charger. By smart scheduling of charging and discharging of both the stationary battery in the house and the EV batteries, the HEMS should not only reduce electricity bills but also increase the house self-sufficiency, since more energy being consumed by the appliances and EV will be produced by PV. In this way, also the house's carbon footprint is reduced

The HEMS technology has been investigated from both the business and technical perspectives. From the technical point of view, four different algorithms have been developed and tested, and a user interface in the form of a customizable smartphone application has been designed. From the business perspective, market and benchmark analyses have been performed, where a set of user personas have been identified and a business strategy has been developed.

Team description by skills

eHome Solutions team is composed of six people of different backgrounds, with the majority of them having received a technical academic education:

- **Attilio Andrea Cuccovillo**, Industrial Production and Technological Innovation Engineering
- **Gianluca Giacomelli**, Automation and Control Engineering
- **Chiara Magri**, Computer Science and Engineering
- **Gianluca Piccoli**, Automation and Control Engineering
- **Matteo Pierini**, Automation and Control Engineering
- **Martina Tosarello**, Architecture for Sustainability

His both Engineering- and Economics-related background allowed Andrea to contribute to the preliminary market analyses, the user personas identification and the development of the strategy.

Gianluca G., Gianluca P. and Matteo employed their education in Automation and Control Engineering in the preliminary analyses of the communication protocols and in the development and testing of the control algorithms.

Chiara worked on the Reinforcement Learning algorithm and tested it, thanks to her knowledge of Artificial Intelligence.

Finally, Martina worked on the realization of the User Interface and the preliminary questionnaire. She was backed by a solid know-how of graphic tools and software, which she trained in her Architecture course of study.

The project has been realized by adopting a sub-team division approach:

- **Business Development**: this area has carried out a market analysis, benchmarking, and strategy development.
- **Innovation**: the main activity of this sub-team has been mapping innovative business models, supporting the Business Development team in benchmark analysis and supporting the Research & Development team in evaluating possible HEMS architectures.
- **Research & Development**: the aim of the R&D team has been the development of the HEMS algorithm.

After six months of work, the group division has been changed in order to allow everyone to focus on tasks which were closer to their academic background.

Goal

The goal of the project is to design a HEMS that automatically monitors and optimizes energy flows in a house to reduce energy purchases from the electricity grid. In this way, the carbon footprint of the house is decreased, and the energy produced by solar panels is exploited optimally. Moreover, the HEMS should deal with the presence of an EV, providing it with the necessary amount of charging and exploiting its battery as an energy storage system. The HEMS is also required to operate with minimal need for manual intervention of inhabitants and to avoid the disruption of daily routines.
The goal presented above can be divided into five main subgoals:

- The analysis of the HEMS market, its complementary systems and communication protocols to do an overall benchmark and understand the related opportunities and challenges.
- The development and comparison of multiple control algorithms, that can schedule energy flows in a house equipped with domestic appliances, a bidirectional EV charger, PV panels, an ESS and a connection to the electricity grid. These algorithms exploit patterns in domestic energy consumption and production, electricity grid prices and EV usage to minimize electricity bills.
- The design of an interactive and adaptive interface, in the form of a smartphone application. The app should allow users to monitor their house energy consumption, the grid electricity prices, and the state of their energy devices. Moreover, it should allow users to express their preferences about the HEMS functioning by setting its parameters.
- The identification and analysis of the HEMS possible customers, together with their needs, expectations and propensity to invest in such a system.
- The outline of a strategy for Free2move eSolutions to develop and spread the HEMS product, both from the technical and commercial point of view.

Understanding the problem

The constant increase of greenhouse gas (GHG) emissions that our planet has faced in the last century has harmfully impacted the equilibrium of the environment, generating the need to shift to renewables. However, renewable energy sources are often unpredictable, and pose the risk of unstableness to the electricity grid, because of its need to always balance energy production and demand. In the meantime, the energy demands of countries are increasing as well, and as a result, an increasing burden is placed on the grid.
According to the International Energy Agency, buildings account for 30% of global energy consumption and almost 10% of CO_2 emissions. Therefore, particular attention should be paid to this sector, and to the opportunities to reduce its environmental impact. The same attention should be paid to the transportation sector, which produces 20% of CO_2 emissions, 40% of which come from automobiles. A possible solution to this issue is the use of electric cars, whose market is steadily expanding. However, the increase in EV sales will worsen the pressure on the electricity grid, as the need for charging batteries could drastically increase overall electricity consumption. This effect is emphasized during evening hours when most people come home from work, and so the peak of residential electricity consumption is reached, which could be exacerbated by the charging of the electric vehicle.
In light of this scenario, the idea of a “microgrid” is gaining more attention as decentralized energy systems, equipped with clean energy generators, could be a viable solution. These microgrids can generate, manage, and distribute energy from various regions, potentially aiding the grid in adapting to the upcoming era. Private individuals and industries can also create similar systems with PV plants, ESS, and communication with the grid. Through the installation of a PV system, it becomes feasible to harness solar energy for either self-consumption or grid feed-in. Energy storage systems can distribute energy generation, typically occurring at specific times of the day, allowing to stock of energy for later consumption. Finally, effective communication with the energy provider can establish their presence in the region as an active energy system and allow them to monitor electricity price trends. However, a pivotal consideration when encouraging individuals to invest in such infrastructures revolves around the aspect of convenience. Energy providers already acknowledge this issue, as they propose tariffs that increase the cost of energy during periods of high demand and vice versa when demand is low. Nevertheless, it remains a complex task for individual users to either sell energy from their battery or acquire energy when it is most advantageous.

From this necessity arises the HEMS, a domestic system designed to optimize energy flows in and out of homes with the ultimate goal of minimizing expenses and losses. With this system seamlessly integrated, it becomes not only possible to synchronize household consumption with the grid to support its stability but also to empower homeowners to substantially curtail their energy bills by managing their available energy resources. Thanks to this innovative solution, participating in the micro-grid system can evolve into not just an opportunity to mutually assist one another but also a financially advantageous prospect for the consumer. Moreover, buying less energy from the grid means reducing the house's carbon footprint, increasing its self-sufficiency, and using more effectively the energy produced by solar panels. If the HEMS integrates an electric vehicle with the residential energy system, it can use its battery as an energy storage system and optimize its charging, in order to reduce its costs and reduce the peak of evening energy consumption.

Exploring the opportunities

A HEMS market study showed that the sector is expected to grow in the next years at a rate of 16.2%. This will happen mainly for two reasons:

- **Governmental regulations:** Regional governments from all over the world have adopted rules and laws aimed at promoting energy efficiency. Because of the increased management of energy by the public sector, businesses, and industries, there is a greater need for energy management systems.
- **Smart appliances' sector growth:** HEMS development and diffusion are connected to the technological improvements of smart appliances. Figure 1 represents how the optimization of smart appliances' functionalities is linked to the growth of HEMS sales. Projections from 2020 to 2030 show that HEMS sales volume will become six times larger, thanks to a great effort in smart appliances' development.

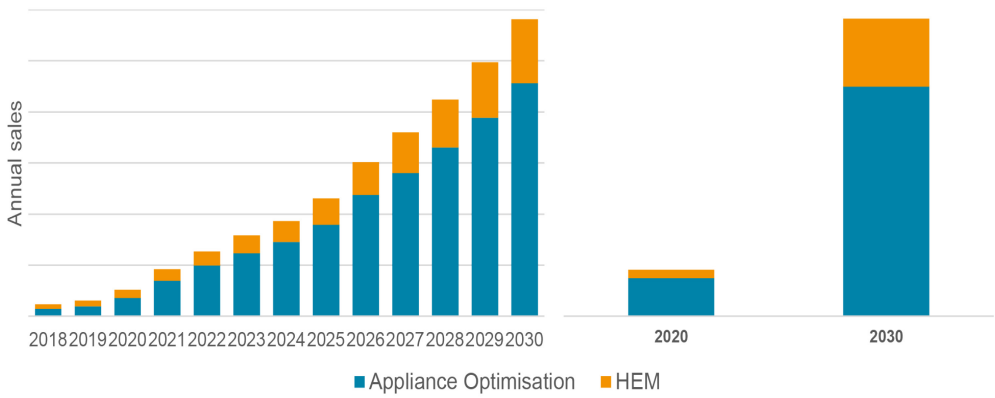


Figure 1. Relationship between HEMS sales and appliances optimization

Additionally, the **competitive landscape** has been analyzed to describe the ecosystem of both HEMS producers and manufacturers of complementary systems (such as EV, HVAC, ESS, PV, or smart appliances manufacturers). What has emerged from this analysis has shown that interoperability between products of different companies is very poor, except in the case of special partnerships where a single app can handle devices from different manufacturers. According to research on this subject, this happens because there is no unified protocol that is compatible with different brands of devices.

Consequently, there is currently **no "comprehensive" HEMS offered by any provider**.

Generating a solution

The first step of the project was the **identification of plausible target customers** through user personas analysis. There are five possible target customers, each one featured by a specific need that HEMS can respond to. In general, the goals of the potential users can range from lowering energy bills to trying new technologies, reducing their environmental impact, controlling and customizing the app and increasing their social status.

Following this analysis, several prototypes of **HEMS control algorithms** have been **developed**. The scope of the work has been restricted to a limited set of devices, to mitigate the problem of interoperability. The considered scenario consists of a house equipped with PV, an ESS, and an EV, which represents a reasonable trade-off between dealing with a limited set of devices and achieving a good performance. The house is powered by the electrical grid, which, if needed, can also be used to sell the excess energy produced by the PV. The proposed algorithms should be able to monitor all domestic energy flows, as well as the grid electricity price, and control charge/discharge rates for the home battery and the EV when present at home. Through the knowledge of the state of the system and, eventually, the prediction of its future evolution, the controller should choose the best control action to optimize some given objectives, which in our study is the energy cost reduction for the final user.

Four different types of algorithms have been developed:
- Perfect optimization
- Rule-based
- Model Predictive Control (MPC) with an ad-hoc EV presence prediction algorithm
- Reinforcement Learning (RL)

According to the simulations made, the most advanced algorithms (MPC and RL) achieved better results, outperforming the base benchmark (Rule-based) by 14% and 7%, respectively. However, since these algorithms' performance relies on large amounts of data and the simulations were run with a limited database, the generalizability of the above results may be compromised. Therefore, from the deployment perspective, it could be better to adopt a **Rule-based algorithm** first (which is able to achieve satisfactory performance while being robust to uncertainties) and move to a more advanced algorithm in the long run when more data is gathered.

Another crucial step of deployment consisted of structuring the interaction between users and the HEMS. The definition of efficient communication between the two parties could determine the technology's success. To reach this goal, a **smartphone app** has been designed.
Given the various intended users, the app was designed in such a way as to accommodate quite different users, in terms of interests and technical expertise. The app redirects the user to the most suitable interface (with more or less features and technical detail) after an initial short questionnaire administered when the app is used the first time.

In conclusion, a **strategy** aimed at defining the necessary steps to develop and spread the HEMS has been defined. Given the constantly increasing size of the smart appliances market, it has been decided to stipulate a partnership with Bosch, one of the biggest players in such a market in Italy. In the agreement, Free2Move eSolutions would be the actual producer of the HEMS, as it would develop the algorithm, the architecture, and the app. On the other hand, Bosch would contribute with its already existing network of domestic integrated home devices, its strong brand recognition and access to a great customer base.
The first 6 months of the partnership are dedicated to product development and testing. Then, some HEMS beta versions are distributed for three months to STEM PhD students at the main Italian technical Universities. The aim is both to collect data from experts and, possibly, enter the tech-savvy market segment. Thanks to the feedback received by the academics, the HEMS can be improved for another 3 months before facing the mass promotion phase. During this stage, two marketing campaigns will promote the HEMS's specific features that satisfy the needs of the user personas identified in the above-mentioned analysis.

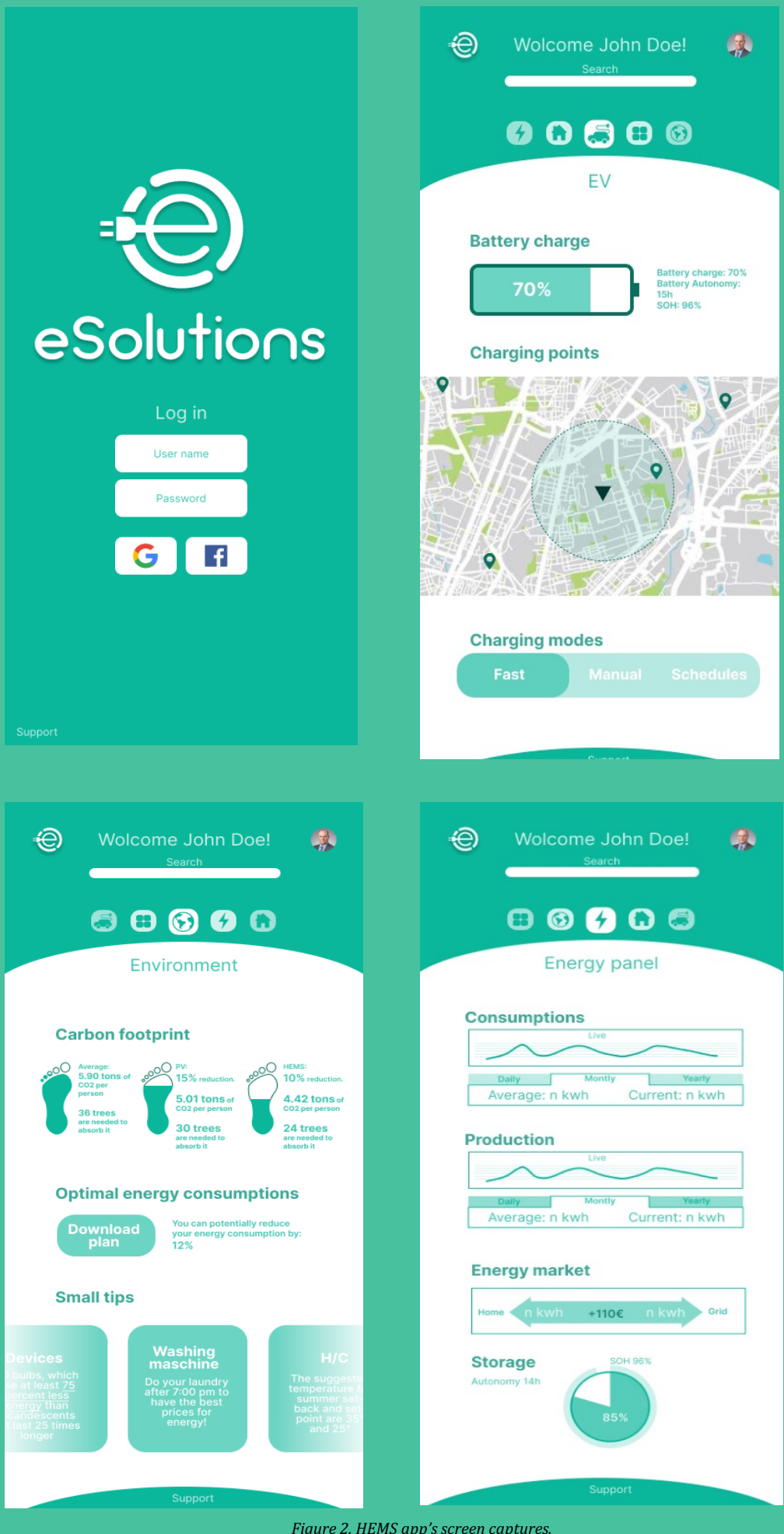


Figure 2. HEMS app's screen captures.

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