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Model predictive control for energy and climate management of a subway station thermo-electrical microgrid

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Abstract

Electricity consumption in urban railway stations accounts for almost one third of the total energy consumption of a subway network of a city like Paris. The overall system's efficiency can be optimized by taking advantage of available sources of energy such as regenerative braking of trains or local renewable energy resources. This can be achieved by handling the intermittent nature of the various sources and consumption points and by redesigning the station energy grid in a global approach.
Microgrids have been an actively researched subject since a few years with the growing interests in smart electricity networks as a mean to decentralize the global power supply facilities. We present hereby a methodology for the optimal management of a microgrid connecting regenerative braking energy sources, eventual distributed energy resources, heating, ventilation, air conditioning (HVAC) systems, specific electricity consumptions and electricity storage systems (ESS) for energy management in subway stations. The overall energy cost is minimized adjusting in real-time electricity demand and availability using demand--response strategies while ensuring an optimal thermal comfort and a safe indoor air quality environment.

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1. Introduction

Urban railway stations consume approximately a third of the overall energy provided to railway transport infrastructures of cities like Paris. We present herein a methodology to optimize the thermal and electrical energy management in a subway station. Our methods are based on a review of the state of knowledge of subway stations energy consumption and production opportunities, a review of thermal, aeraulic and electrical modelling of subway stations as well as innovative technologies and techniques to store and manage energy.

The control, or management, strategy is based on Model Predictive Control (MPC), an online dynamic optimization method, which computes nearly optimal strategies for both power dispatch and HVAC operation impacting thermal comfort and indoor air quality. The control strategy involves a detailed thermo-electrical model representing both the behavior of the grid from an electrical point of view, the building temperature dynamics and the indoor air quality evolution. It consists in minimizing a cost function measuring the energy cost and the gap between the desired temperature and air quality at some points and the model's response. Appropriate constraints on control variables are considered in this paper. This continuous time optimization problem is solved using an adjoint-based approach and the Levenberg Marquardt algorithm which is provided and built in the energy optimization and simulation software toolbox Retrofit. It enables a fast resolution of the problem for a sufficiently large prediction horizon and a small time step between control policy generations producing a feedback mechanism addressing the microgrid uncertainty issues.

The whole methodology is applied to a test subway station. Simulation results using existing and experimental station data are provided to a priori assess the performances and reliability of the optimization, MPC scheme and of the microgrid with respect to the actual energy management strategy. We briefly introduce the experimental campaigns under way in order to highlight the experimental conditions of our tools.

2. Energy in subway stations

2.1. Energy consumption

Some measures campaigns have been conducted to understand the consumption profile of each electrical equipment in a subway station. It appears that the amount of energy required for the HVAC systems and the escalators represent an important part of the total energy consumption in various subway stations. The total daily energy consumption of a Paris subway station may vary between 1MWh and 3MWh based on these studies results.

Researchers of the European project OSIRIS (Turkay et al. 2015) noticed that a network energy consumption profile over a day is correlated with passenger traffic during operating hours. In particular there are peaks of power demand during passenger traffic peak hours. A scatter plot of electrical consumption over passenger traffic made by RATP displays a clear linear tendency. The energy contract of Paris subway stations main operator, RATP, displays two tariffs distinguished by a power threshold. Under a particular power consumption the price of electricity per unit of power is low, on the opposite when this limit is reached the tariff is high. Therefore during peak hours the operator consumes a large amount of energy that is more expensive than during off-peak hours. Lowering peak hours consumption could consequently lead to significant economic savings. Shaving peaks is often described as a major objective of smart grids. It is in fact a heuristic of judgment. It seems obvious that shaving peaks will provide economic gain but what we are looking for is the best economic gain or savings. There's an important probability that the economic optimization of the grid will lead to shaved peaks but that's not our direct objective. Letting an optimized controller generate an appropriate command law is what makes an electrical grid smarter.

2.2. Energy production opportunities

A subway station and its railway environment are not exclusively energy consumers, there exists some energy production opportunities due to its specific architecture and functions.

Some electrical power may be produced by different means:

- Local renewable energy resources: Photovoltaic panels on the roofs of surface stations for example could provide an important quantity of energy to respond to the energy demand.
- Regenerative Braking: Regenerative Braking consists in converting the mechanical or kinetic energy of a subway into electricity. Obviously converting a kinetic energy into electricity implies lower speed, therefore this electricity is produced during the train braking phase. A significant portion of the braking energy is already recovered as electricity and shared with the other trains of the line. However it appears that there still exists a large amount of energy dissipated by mechanical braking (rail friction) and eventually resistors. The energy deposit constituted by regenerative braking is substantial over a subway line. If a station happened to be equipped with an electrical storage system it could save up to two third of electricity over a day using braking energy. Of course this energy would be available for one single station of a line. González-Gil et al. (2014) assessed innovative ways to improve energy efficiency of subway stations recovering regenerative braking and produced an investment-benefits diagram to sum up their results (González-Gil and R.P., 2014).

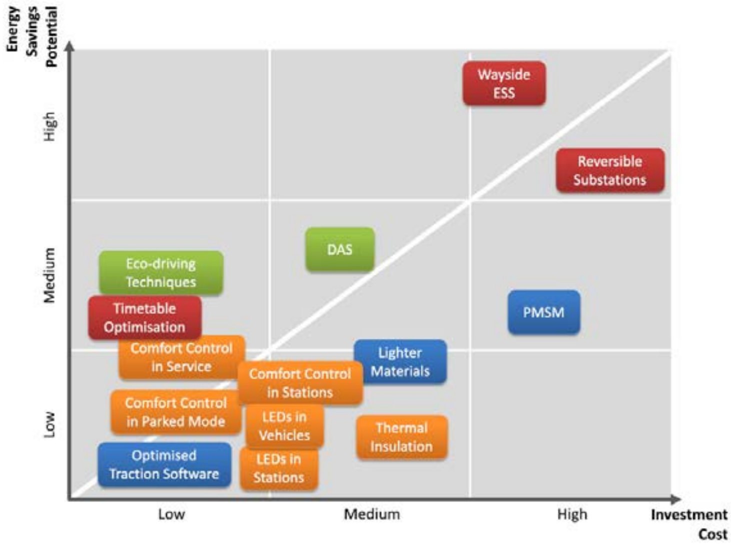

Fig. 1. Levers to improve energy efficiency of subway stations (González-Gil and Palacin, 2014).

It appears in figure 1 that electrical storage systems constitute the second most expensive investment but it’s also the best way to realize economic savings.

Some thermal energy can be produced as well:

- Fatal thermal energy: Heat recovered from technical facilities and mechanical braking remaining and cold from Canadian wells like installations to cool the technical facilities can represent the total amount of energy required to keep every rooms temperature of a station in good thermal comfort and technical operations conditions. A subway station of RATP network provides good example of the fatal thermal energy potential of subway stations. This station is built in groundwater with double walls constituting a cold air deposit trapped between a diaphragm wall in contact with cold groundwater and another one separating the “Canadian well” and the station. The air can be naturally or mechanically ventilated to the subway stations facilities. In this station the residual heat dissipated by technical facilities represents a potential of about 30 kw of thermal power, which is substantial.

- Local renewable energy resources: Geothermal energy can be harvested by geothermal wells and heat pumps and can provide some additional energy to fulfill the station needs and distribute thermal energy to the close neighborhood. The architecture of subway stations is an opportunity for such equipment as they are underground places with deep underground structures like foundation piles.

Subway infrastructures provide interesting energy production opportunities however the electricity production provided by braking trains is not yet fully exploited as the power profile is extremely variable due to several uncertainties (mainly speed profile) and an electrical circuit limit due to voltage stability of the line. These kinds of issues are already faced by speed profile optimization on automated lines and electrical storage equipment by different stakeholders of the electricity market (Yang et al. 2014, EDF-RE 2015) but few transportation companies (Conti et al. 2015).

2.3. Energy storage and subway stations demand response

Batteries as well as super capacitors can provide an efficient way to recover a larger amount of electricity from braking trains. This is explained by considering the receptivity of the line which is defined as the amount of electrical energy recovered over the amount of electrical energy recoverable. This indicator is highly dependent of the subways timetable which already minimizes the number of trains required to ensure the best quality of service possible. However, during off-peak hours, the lack of synchronization due to the low number of trains implies a significant amount of electrical losses. The electricity offered by a braking train has to make its way over a long portion of cable in order to meet an accelerating and power demanding train. Fig. 2 (Capasso et al. 2010) displays the receptivity (recovered energy over recoverable energy ratio) variations when the headway and time-shift between trains vary. We notice that during peak hours (small headway = "cadenzamento") the receptivity is at its highest value. An electricity storage system provides an almost constantly available power demanding equipment. A battery could be used for voltage regulatory purposes to prevent such losses. As a consequence an electrical storage potentially improves the receptivity of the line, lowers the electricity losses and proportion of mechanical braking (González-Gil and R.P. 2014, Conti et al. 2015).

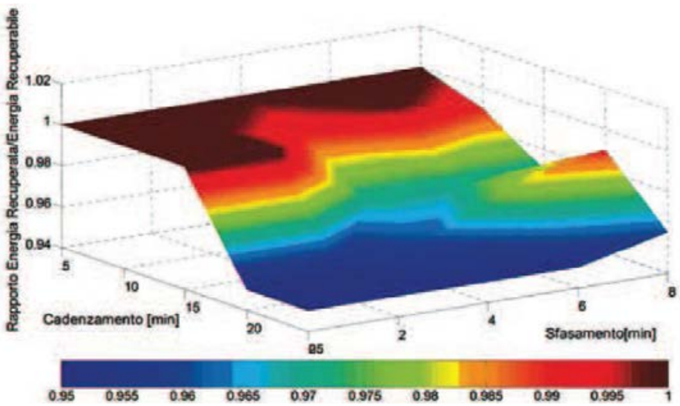

Fig. 2. Receptivity as a function of headway and time-shift (Capasso et al. 2010).

Buildings indoor environment could be used the same way to store heat as a thermal battery. This energy would be reused later as its original form: heat, just as electrical storage. Of course we don't control indoor temperature dynamics as we do for batteries but we highlight here that both aspects give leverage to ensure the energy demand/offer equilibrium. Thanks to them we can provide a Demand Response, or demand side management, to an electricity offer signal which is a concept at the very core of smart grids (Siano et al. 2014, De Lara et al. 2014).

2.4. A subway station test case

In order to assess our methodology and tools we defined a simple test case sufficiently detailed to provide reliable results but not as detailed as our objective.

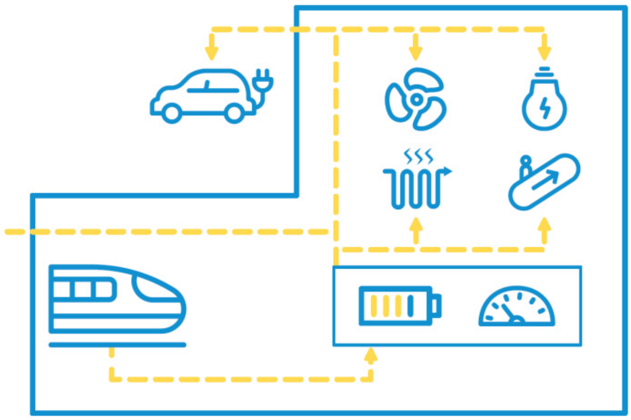

Fig. 3. A simplified subway station.

Our simplified case consists in a subway station modelled as a unique room and equipped with subway trains providing regenerative power, a battery, indoor heat gains, a mechanical stairway, a mechanical ventilation and lights. The whole grid is connected to the national energy supplier grid.

3. Subway stations dynamics modeling

In order to make grids smarter we need to provide the controller device a way to observe the controlled system. That is why modelling and measuring/monitoring are essential for smart energy management.

3.1. Thermal dynamics & thermal comfort

Building thermal dynamics modelling is an important area of research which is gaining more and more interest as we tend to improve energy management at the building scale with concepts like smart buildings, smart home and positive energy building. A subway station is a specific building that totally benefits from building modelling techniques. Several studies have been conducted to model the thermal behavior of a subway station (Ampofo et al. 2004, Khalil et al. 2013). Different levels of details are possible to model building thermal dynamics. Highly accurate techniques like Computational Fluid Dynamics (CFD) tend to model precisely the dynamics of the indoor air characteristics and flows and have been applied to subway stations aeraulics modelling (Khalil et al. 2013). Such models require a detailed space discretization and a high computational effort which often prevent using them for real time purposes. There exist less detailed models compatible with real time objectives (Lin et al. 2014). Multi--zone modelling is a good compromise between accuracy and computability that allows to address a dynamic optimization problem. In our test case the thermal dynamics model links indoor temperature $T(t)$ to outdoor temperature $T_e(t)$, ventilation consumed electrical power $P_V(t)$ and indoor heat gains $Q_H(t)$. C_V is defined as the thermal capacity of the subway station and r_V is the efficiency of the electrical to mechanical conversion of the ventilation. Knowing these dynamics we will be able to control some aspects of thermal comfort by changing indoor/outdoor air exchange and eventually heat in exploitation facilities.

$$C_V \frac{dT}{dt}(t) = r_V P_V(t)(T_e(t) - T(t)) + Q_H(t) \quad (1)$$

Thermal comfort modelling is strongly linked to thermal dynamics modelling and relies mostly on a model created by Fanger (Charles et al. 2003). This model is called PMV/PPD (Predicted Mean Vote/Predicted Percentage of Dissatisfied) and provides indicators to predict the mean thermal appreciation of the occupants of a room or building. This model comes with official norms defining a good thermal comfort for buildings. Some studies have been made to select the best thermal comfort model for subway stations or naturally ventilated buildings. Ampofo et al. 2004 and Abbaspour et al. 2008 for example observe that the PMV/PPD is a good choice for subway stations if we lower the requirements provided by general buildings norms like ASHRAE 55 2013 or ISO 7730-2013. For the sake of simplicity thermal comfort in our test case is currently modelled by temperature constraints, a more detailed model will be tested in the future.

$$T_{\min} \le T(t) \le T_{\max} \quad (2)$$

Campaigns have been conducted to expand our knowledge of subway stations climate. They consisted in temperature and relative humidity measures and display similar results. Measurements to compare our results and calibrate our models are provided by RATP at the station Front Populaire. Less detailed measurements made by the RATP SQUALES network in 3 subway stations Auber, Chatelet-Les Halles and Franklin D. Roosevelt are publicly available (RATP 2015).

3.2. Airborne particles and aeraulic dynamics

Air quality is a major concern in subway stations therefore several campaigns have been conducted to measure air quality, to compare particles behavior to models or to simply understand their behavior and major sources. Moreno et al. 2014 for example demonstrate that the decision to use a mechanical ventilation for particles or not should rely on the station architecture because a ventilation in a two ways tunnel could make the air quality worse. In this case the train piston effect could be enough to clean the air. These studies show that airborne particles in subway stations are mainly ferrous particles coming from brakes wear over rails. Generally all the studies demonstrate that CO, CO_2 and NO_x are not a concern for subway stations except in rare events (New Year's Eve high frequentation, reparation requiring a fuel train…). Data to apply and compare our results and calibrate our models is provided by RATP SQUALES for the 3 subway stations of the SQUALES network.

Several studies focus on the aeraulics modelling of subway stations as airborne particles are a major health concern of indoor air quality experts and because trains brakes wear implies an indoor source of ferrous particles. Some studies provide detailed models of indoor particles behavior thanks to computational fluid dynamics (Khalil et al. 2013, Camelli et al. 2014, Di Perna 2014). These articles assess the quality of CFD models and some provide a methodology to control mechanical ventilation along with these detailed models requiring high computational performances.

Health impacts of this kind of particles are under study then we focus here on the research describing their behavior in subway stations and methods to lower their quantity.

A simple PM concentration dynamics model is proposed by McGrath et al. 2014 and roughly consists in the same dynamics as indoor temperature. It is applied to a single zone with outside air infiltration in our test case. Q_{PM} represents the indoor particulate matters concentration while $Q_{PMe}(t)$ is the outdoor concentration, $Q_{PMtrain}(t)$ is the PM gains due to subways brake pad wear, V is the subway station air volume, $r_{\inf}$ is the infiltration coefficient, S_S is the surface of the station (including floor, walls and ceiling) and v_g is the deposition velocity of the particulate matters. It is assumed that the trains of the line produce a volume $k_{wear} \cdot W_{wear}$ of particles in the air with $k_{wear} \approx 2.10^{-13} m^3 / J$ (Conti et al. 2015).

$$V\frac{dQ_{PM}}{dt}(t) = r_V P_V(t)(Q_{PMe}(t) - Q_{PM}(t)) - \nu_g S_S Q_{PM}(t) + V * Q_{PMtrain}(t) \tag{3}$$

And the PM concentration is of course constrained to stay between two air quality bounds.

$$PM_{\min} \le Q_{PM}(t) \le PM_{\max} \tag{4}$$

3.3. Electrical power dynamics

Electrical power dynamics modelling is a really mature area of research and providing well known techniques to model electrical and electronic gears. A high level energy management system optimization requirement is a simple but good model of the electrical storage system dynamics. We developed such a model for the battery of the subway station. For the sake of simplicity and to ensure a good ageing of the battery we constrain the state of charge to remain between two bounds. These bounds depend on the technology and define the lower and upper limit of the battery state of charge dynamic linear behavior. This model coincides with simple models often used in energy management optimization problems. The state of charge $S_{OC}(t)$ depends linearly of the battery charge/discharge power $P_B(t)$ the charge/discharge efficiency ρ_B, the open circuit voltage V_0 and the battery current charge $Q_{\max}$.

$$\frac{dS_{OC}}{dt}(t) = \frac{\rho_B}{V_0 Q_{\max}} P_B(t) \tag{5}$$

Electrical measures devices are quite recent but numerous technologies are emerging with the growing concerns of electricity consumption. Companies like Smart Impulse provide non-intrusive devices to measure the electricity consumption of each electrical equipment. A partnership with Smart Impulse and RATP permits to obtain real time measurements of a subway station of Paris subway network (Smart Impulse, 2015).

The previously described dynamics characterizing subway stations are coupled in an energetic and comfort aware paradigm. A key feature of every energy management problem is the power offer and demand equilibrium. If $P_G(t)$ is the power taken or provided to the grid, $P_{Train}(t)$ is the power produced by trains and $P_{NC}(t)$ is the non--controllable electrical demand, this equilibrium is formalized in (6).

$$P_G(t) + P_{Train}(t) = P_{NC}(t) + P_V(t) + P_B(t) \tag{6}$$

4. Subway stations energy management

A good knowledge of our objectives and the simple models developed allow to define an optimization problem providing, after resolution, an optimized strategy to manage energy and climate in a subway station. However as we modelled dynamics of the building and the electrical devices, the optimization problem is not a static one. We need to explore a dynamic optimization/optimal control framework to define a suitable strategy for our problem.

4.1. Model Predictive Control

Model Predictive Control (MPC) is an approximate dynamic programming approach allowing to compute controls online. The idea of this type of method is to compute an open loop control law for a finite optimization horizon, for example 24 h. The control law is then applied until the next optimization step (for example 5 minutes later), sensors data is observed and the problem is re-optimized in order to compute a new control law over 24 h. This strategy allows to obtain a global policy with state feedback by solving open loop problems regularly. MPC is a simple way to obtain a near optimal control policy bringing a solution to the “curses of dimensionality” and usual dynamic optimization issues like state constraints and nonlinearities as the online subproblem is solved thanks to thoroughly developed mathematical programming techniques (Bertsekas 2007, Powell et al. 2015).

4.2. Optimal control problem

In order to apply a MPC strategy we defined the subproblem that will be re-optimized at each optimization step. It's an open loop optimal control problem which means that the controls are only time dependent. The optimal control problem sums up the models we previously introduced as constraints to the minimization of the energy economic cost for the subway station operator. This problem displays a quadratic objective but some nonlinear constraints as well as state variables constraints. These aspects are difficult to handle in an optimal control framework but integrate smoothly in a more general mathematical programming framework. The quadratic objective function provides the insurance that the MPC scheme is stable and relies on the mature theory of linear quadratic control. The problem states variables box constraints are penalized, the dynamic constraints are handled using the adjoint problem allowing a fast computation of the gradient and the problem is discretized using finite elements leading to a constrained quadratic program. A projected Levenberg-Marquardt algorithm, implemented in the Energetic and Thermo-Dynamic Simulation and Optimization Matlab® toolbox Retrofit®, is used to approach a global optimum of the problem (Nassiopoulos et al. 2014). The quadratic objective function is formulated in a way that the resolution of the optimization problem tends to minimize the cost of consumed electricity without preventing the cost to drop below zero. Selling electricity to the national grid is therefore theoretically possible, the price per unit of power is denoted $C(t)$ but in our first results we consider that a negative energetic cost corresponds to an unused energy (dissipated by heat or mechanical braking).

$$\min_{u \in U} J(u(t)) = \int_0^{\tau} \max(0, C(t)P_G(t, u(t)))^2 dt \qquad \textit{Subject to.} \qquad (1) \text{ to } (6) \qquad (7)$$

$u(t)$ being the control vector at each instant containing every control variables, here $u(t) = (P_V(t), P_B(t))$.

5. Results

5.1. Current situation vs. ESS equipped station recovering braking energy

This use case applied to our subway station test case provides encouraging results concerning battery control. We compare here a subway station with a simplified electricity consumption profile over a weekday and a subway station with the same profile but equipped with a 480 kWh battery allowing braking energy recovery and optimal energy management throughout the day. The state of charge is constrained to remain between 40% and 80% to ensure good ageing of the battery. We adopted a simulated high weekday braking energy production profile with a current limitation of 600A due to supercapacitors limitations. We chose a forecast horizon of 20 hours (a normal day of subways operations between 5am and 01h00 am), with a discretization time step of 5 seconds which is overly cautious compared to existing operational microgrids energy management strategies (Biyik et al. 2014). The cost of electricity per Watt C(t) is assumed only time dependent. According to its definition it must depend on the total power consumption of the operator over its whole network, which is far more important than a single station consumption. C(t) is therefore considered exogenous. The demand profile is provided by measurements made by Smart Impulse in a RATP subway station. The control variable (battery power) is subject to regularity constraints (it must belong to the sobolev space $H^1(\Omega)$) to prevent fast high variations for the battery. Assuming that the forecasts are 100% accurate, we observe that a battery controlled over 20h could lead to up to 32% of energy savings and 34% of economic savings compared to the current stations energy management. The original investment of an electrical storage system is not considered here. Energetic profiles over 20 hours (72000 seconds) of the results are displayed figure 4. We observe on the first plot really fast variations of grid consumption filling the space between the envelope and the x axis. Such an electrical behavior is a consequence of the regularity constraint applied to the battery that uses some grid power to keep charging between two braking energy peaks. Other results with a softer constraint (u must lie in the Sobolev space $L^2(\Omega)$) or no regularity constraint display similar or better results. The “no constraint” case provides up to 45% economic savings but with really fast variations of battery power that might be harmful for power electronics. Appropriate constraints are being defined by further studies on power electronics, batteries, supercapacitors and national grids power variations limitations. The results are produced assuming a perfect knowledge of the future, it produces therefore an inferior bound on the real solution (as we are minimizing) but permits to test the resolution method of the constantly reoptimized problem in the MPC scheme. We expect similar results in a real case as the uncertainties regarding trains timetable are small. The time resolution of this problem gives an insight on which reoptimization time step we must choose for our microgrid. 15 minutes might be a good time step here, it is a short enough time window for existing microgrids high level energy management systems (Biyik et al. 2014). The nonlinear problem is solved by Levenberg Marquardt algorithm, other algorithms will be implemented in the future to speed up the resolution of the nonlinear problem.

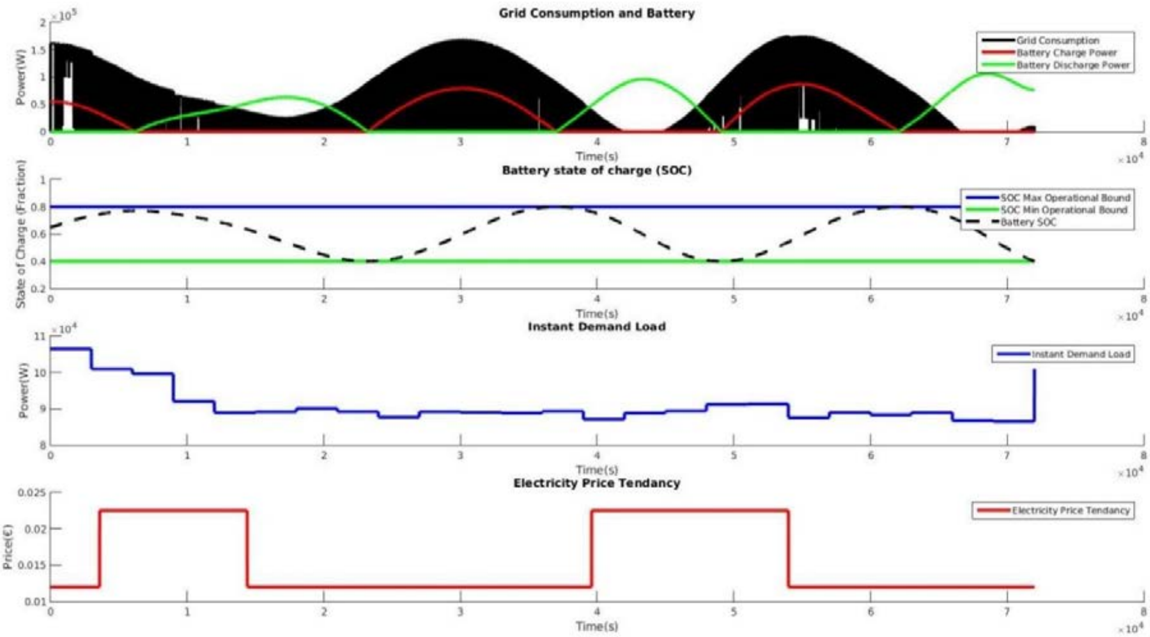

Fig. 4. Energetic profiles of a subway station equipped with a controlled battery.

A recently implemented dynamic programming algorithm provides results leading to up to approximately 50% of economic savings over a day.

6. Conclusion

The Microgrid concept brings a new opportunity to optimize the energy and climate management of a subway station. Electrical storage systems provide innovative ways to fully exploit the potential of regenerative braking energy generation of a line for a single station as well as air quality improvements and more energy efficient ventilation control strategy for every stations of a single line. This must be achieved by a proper understanding of subway stations thermal, aerodynamics, electrical and even architectural specificities. These studies of subway stations benefit from the vast literature focusing on building thermal and indoor air modelling, substantial recent interests in electrical storage systems, electrical and economics models as well as the large theory of optimal control. Our predictive model based control strategy called Model Predictive Control has been tested on a theoretical subway station with simplified characteristics and with simulation results. The first results of our high level energy management strategy are promising and display significant economic savings that could at least balance the battery initial investment.

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