Smart house energy management project ELEN90088 Starter kit

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Overview

The general idea of this project is to practice your optimisation and machine learning knowledge on energy and power systems. While this document makes a range of suggestions, it is up to you to tailor your project for best possible learning outcomes in ELEN90088.

One possible idea is to develop the control algorithm for a Home Energy Management System (HEMS) for a smart house equipped with solar photovoltaic (PV), battery energy storage system (BESS), and an electric heat pump (EHP), which uses electricity to meet the demand for heating and/or cooling of the house.

For a given house with its base electricity demand profile, outdoor temperature profile, insolation profile, and expected energy prices, the objective of your HEMS controller will be to optimally schedule the charging and discharging of the BESS and the temperature setpoint of the EHP in order to minimize the electricity bill of the house while meeting preset comfort constraints (e.g., min and max acceptable indoor temperature) as well as other physical constraints (e.g., max power that can be injected into the network).

You should be able to use some of the constrained optimization techniques you are learning in the course to determine this optimal schedule, including simple approaches such as linear programming. Note that the BESS and the house fabric's thermal inertia represent two different forms of storage, so when you design your algorithm, you will need to consider inter-temporal constraints that link different timesteps via the relevant dynamics of the BESS and the house.

Furthermore, as the base electricity demand of the house (e.g., lighting, TV, computers, etc.), the insolation level (that determines the PV generation), and the outdoor temperature (that will drive the requirements for heating/cooling) are all uncertain, you will need to set up some predictive intelligence to be coupled to your scheduling algorithm. You will thus be able to use some of the machine learning (ML) techniques you are studying in the course. Depending on the market context of your house, especially looking at a future smart grid setup, electricity pricing may be varying with time and future prices may also be uncertain. Finally, you might also be requested (at relatively short notice) to limit the max power you can inject into the network to avoid grid issues. All of these will add more interesting features to your work! 😊

Useful information

This starter kit will help you find relevant information and datasets to conduct your project successfully.

Home Energy Management System

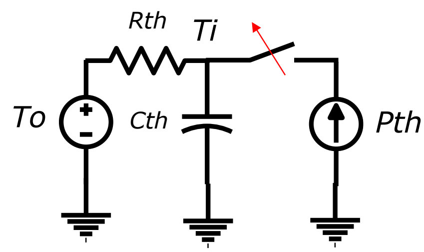
For the general idea of a HEMS and how it can deal with scheduling with different types of appliances subject to uncertainty and comfort level constraints, you may have a look at Althaher et al. "Automated Demand Response From Home Energy Management System Under Dynamic Pricing and Power and Comfort Constraints", *IEEE Transactions on Smart Grid*, 2015:

https://www.researchgate.net/publication/273769918_Automated_Demand_Response_From_Home_Energy_Management_System_Under_Dynamic_Pricing_and_Power_and_Comfort_Constraints

But do not worry too much, your schedule algorithm may be much simpler than the one in the paper and still be very successful! There are also plenty of other references you can find on the internet, including actual commercial products.

Simple house thermal models

In the paper by Althaher et al., there is a simple first-order thermal model of a house, which can be represented as an RC electrical equivalent. In this model, temperatures are mapped into voltages and thermal power flows (heat) are mapped into currents. Hence, R represents the house thermal resistance between indoors and outdoors, which opposes the exchange of thermal energy, that is, the current, and C represents the thermal capacitance of the house (the thermal "inertia", which also opposes changes in the indoor temperature, that is, the voltage – think of the classical time constant of an RC circuit). The indoor temperature is a variable that you need to keep within predefined limits via scheduling thermal power exchanges with your EHP (which you may switch on/off or modulate, depending on the specific type). In the electrical equivalent, the outdoor temperature is a time-varying ideal voltage generator (the outdoors is so big!) which represents a "disturbance" that causes thermal power to escape through the resistance. Effectively, your HEMS controller has to schedule EHP operation so that the thermal power from the heat pump can compensate for the building's thermal power exchange with the environment outside according to the circuit's dynamics.



The simplest electrical equivalent of a house thermal model

Additional information on (more complex) RC models of a building and other general information about building models may be found in the paper by N. Good et al., "High-resolution modelling of multi-energy domestic demand profiles", *Applied Energy*, 2015:

https://www.researchgate.net/publication/267454855_High_resolution_modelling_of_multi-energy_domestic_demand_profiles

The book by the, alas recently passed, Prof David MacKay is also a huge source of critical knowledge and information (everyone should read this book!), including on building thermal models:

https://www.withouthotair.com/c21/page_140.shtml

and on his own house!

A famous house; Prof MacKay's one.
Source: D. MacKay, "Without the Hot Air", https://www.withouthotair.com/

Residential solar PV

For solar PV, again you may have a look at MacKay's book:

https://www.withouthotair.com/c6/page_38.shtml

and

https://www.energy.gov/eere/solar/solar-photovoltaic-technology-basics.

For something a bit more technical, the book by G. M. Master, "Renewable and Efficient Electric Power Systems", Wiley, 2013, is an excellent textbook (it should be freely available in the university library).

In particular, if you want to understand and model better the actual performance of a solar PV, you may want to model the PV sun-to-electricity conversion efficiency as a function of the temperature too, as the efficiency drops when it's really hot (and fortunately there's lots of sun too).

One thing you'll need to do is to size your PV panel in a way that makes sense subject to a number of physical constraints. Starting from the size of the house rooftop. And of course, you may want to do some research about the typical sizes of residential PV.

Electric heat pumps

To learn more about EHPs, some information can be found here:
https://www.engineeringtoolbox.com/heat-pump-efficiency-ratings-d_1117.html

https://www.energy.gov/energysaver/air-source-heat-pumps

https://www.withouthotair.com/

There are also plenty of textbooks, e.g., the books by Mancarella and Chicco "Distributed multi-generation systems: energy models and analyses", Nova, 2009, and by L.D. Danny Harvey "A Handbook on Low-Energy Buildings and District-Energy Systems Fundamentals, Techniques and Examples", Routledge, 2006, both also available in the university library.

Something interesting to consider in your model is that the efficiency of an EHP, measured by the so-called coefficient of performance (COP) that reflects the efficiency of converting electricity into heat, is also a function of the outdoor temperature (as well as the indoor one). The "split" air conditioning systems that you find more and more in houses in Australia and worldwide are indeed, basically, reversible air source EHP that can do both heating in winter and cooling in summer, and their COP may change significantly with the temperature. Simply put, when it's really hot outside, an EHP struggles to provide cooling and consumes more electricity; similarly, it struggles to provide heating when it's really cold. Hence, interestingly, when for example it's really cold you need more heat but because the COP will drop, you'll also need to buy more electricity in a disproportional way.

As for PV, you'll need to consider how big an EHP you need to meet the thermal demand of your house. For which you need to look at the physical characteristics of your building (e.g., the RC parameters of your building model) and the kind of worst-case conditions you may find in winter (for heating) and summer (for cooling) in the relevant location you choose. Cooling may be optional, but generally, we do not want to do without heating in a cold winter…

Residential battery energy storage systems

General information on BESS can be found here:

https://arena.gov.au/renewable-energy/battery-storage/

A datasheet example for a small-scale, residential battery (well suitable for your project) is:
https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwall%202_AC_Datasheet_en_AU.pdf

However, of course, feel free to do your own research, especially if you plan to buy one for your own place 😊.

You'll need to look into the best possible size for your battery, also linked to your PV panel, for which again you may want to look up typical sizes available in the market, average sizes of batteries in Australia, etc.

Model predictive control

Your BESS and EHP scheduling algorithm have to be developed some time ahead to try to optimize the utilization of electrical and thermal storage. However, while you can develop a "deterministic" algorithm where you assume that you know with certainty all the future parameters, in reality, you must consider forecasts (on temperature, insolation, etc.), given the presence of various uncertain data. Therefore, an option would be to make your deterministic model more "robust" and integrate it within a model predictive control (MPC) algorithm.

In its simpler form, an MPC algorithm assumes that you know future trajectories of your uncertain parameters (they are in practice a "point forecast" that you may determine through different ML approaches) for several time steps over which you perform your inter-temporal optimization. Then your prediction and optimization horizon "rolls over" to the next step and repeat your exercise for the next time step with updated information you'd receive in the meantime. That is why the MPC approach is also called the "receding horizon".

An interesting set of lectures about MPC can be found here:
https://www.youtube.com/watch?v=kM7W9QaGd1E (Part 1)

https://www.youtube.com/watch?v=k8UvEGZWGD0 (Part 2).

As you will see from these lectures, the simplest form of MPC is kind of "deterministic", as it is based on projections of one scenario/trajectory based on point forecast, as aforementioned, and depending on your system model the relevant optimization algorithm may be linear or nonlinear. Also, aspects such as the incorporation of the comfort level expectation can be modelled as more or less "soft" constraints and in that case, as a part of the objective function through penalty terms, to help with the numerical aspects of your algorithms.

Other, more complicated forms of MPC could also be implemented to deal with uncertainty, e.g., *stochastic* MPC, based on multiple scenarios or *robust* MPC, based on worst-case scenarios. It's your choice to decide what the best approach is to deal with your HEMS problem, but just for you to know we would generally be happy even with the simplest approaches (e.g., linear MPC), as long as it is well developed and explained and, of course, works! Finally, feel free to look into other sources to learn more about MPC, from textbooks to the good old Wikipedia:

https://en.wikipedia.org/wiki/Model_predictive_control

Prediction, machine learning and ex-post validation

The ML techniques that you are studying in the course will be coupled to your optimization algorithms and can be used to estimate temperature profiles, PV production, household base electricity consumption, etc. In addition, as the COP of an EHP, both for heating and cooling, and the conversion efficiency of PV both depends on the outdoor temperature, which will of course influence the heating/cooling demand too, a good estimation of the temperature will be really important (together with your estimation of insolation and in case energy prices too, of course)! Therefore, an interesting exercise for your project will be to analyze ex-post how the accuracy of your "estimators" will impact the overall costs and the way you can actually meet constraints (in case you are considering soft constraints too).

Relevant data sources

Base electricity consumption

In order to develop a proper HEMS, you'll need to have some information about the base electricity consumption from appliances such as lighting, computers, etc. The base electricity profiles aggregate together the (non-thermal) appliances you may find in a house, and that is why there are lots of spikes, cycles, etc., as that is how kettles, washing machines, etc. work.

There are multiple electricity load generators online, e.g.

https://www.utwente.nl/en/eemcs/energy/profile_generator/

https://www.loadprofilegenerator.de

You'll then have to develop your own building thermal model and calculate the electricity consumption profile of the EHP to generate the required thermal energy, and the EHP electricity consumption will have to go on top of the basic electricity consumption profiles.

You will have to use the base electricity profiles, the EHP electricity profiles, and the total electricity profiles to train (and test) your prediction algorithms and improve the overall scheduling of EHP and BESS, considering that your HEMS would not know in advance what you are going to do exactly. You should think of the information that in practice the HEMS could gather in the house to identify the best way to use the different profiles.

Outdoor temperatures

You'll need outdoor temperature data to create your profiles of thermal consumption for your house.

You can find recently recorded temperature data for any location here:

http://www.bom.gov.au/climate/data-services/station-data.shtml

For example, you might want to use the historical temperature data provided to train your ML predictive algorithms and then test them with recent data that you would collect yourself.

Of course, feel free to use any other temperature dataset that you might find, as long as it is useful to achieve your project aims.

Indoor temperatures

You then need to also make some assumptions about the indoor temperature that you want to maintain inside your house to keep a certain comfort level. For example, 21°C in winter and 23°C in summer could be suitable "setpoints" to maintain in your house (but again, this is quite personal, isn't it?).

Normally there is also a "deadband" of around ± 1°C or ± 0.5°C to create some headroom in the way your EHP operate. The deadband normally depends on the thermal inertia and heat losses of the house, the acceptance of and sensitivity to fluctuating indoor temperatures in a relatively short term, and how convenient or even possible it is to cycle your EHP and controller. You can read more about this in the Applied Energy paper by N. Good et al. that was mentioned before.

In the context of energy bill reduction, one could actively play with all these parameters in your optimization algorithm and HEMS. For example, one could "reduce setpoint and reducing it in winter if there's a period of increasing prices or increasing it in summer for the same reason. Of course, you might want to do this only in special occasions, your call! You could also play with the deadband and create "flexibility" by increasing the deadband to ±2°C or even ±3°C, to do things such as "pre-cooling" or "pre-heating" in the case these strategies make sense for time-varying prices.

If nobody's at home, or while you're sleeping, you might not necessarily want your house to keep running particularly warm in winter or cool in summer. So you might decide to set up the EHP operation schedule and link it to the house occupancy level (no need for heating/cooling when nobody's at home!) or to the day/night cycle. In fact, during the night, comfort level requirements are generally different from during the day. So for example, in winter, when you sleep, you may want to have (much) cooler rooms than when you're active, say at 17°C. You can then set up time-differentiated setpoints during the day and night, e.g., 17°C for 10pm-5am and 21°C for 5am-8am and 5pm-10pm. Here I am also assuming that you'd be going to the office or the university at around 8.30am or 9am and come back at around 5.30pm or 6pm. How different would it be if you were working and studying from home?

While you might also decide to simply switch off your heating system during the night or when you are at home, in this case, it might also be a good idea to have a "setback" temperature in your control system, for example not allowing the temperature in the house to ever drop under 15°C in winter or increase to more than 30°C in summer (these are just examples…).

Insolation

Like temperatures, you need information about insolation levels to estimate PV production. Information on insolation profiles in different sites around the world (included very close to where you live, in case you are thinking of buying a PV panel and directly contributing to decarbonization!) can be found here:

https://pvwatts.nrel.gov/

Alternatively, 1-min resolution historical insolation profiles are available (free of charge, starting from the year 1999) on the Bureau of Meteorology website:

http://www.bom.gov.au/climate/data/oneminsolar/about-IDCJAC0022.shtml

To access the data (open access, .txt format) you are required to register. The system will then send an email with a username and password.

It is convenient and most desirable to have a consistent dataset for temperatures and insolation if you want to simulate something as realistic as possible.

Prices and tariffs

Prices to residential customers may be available in different ways. The simplest way is of course *tariffs*, which can be of a different type. Just to have an idea, you may have a look at:

https://www.originenergy.com.au/pricing/explained/

Tariff differentiation and options will also become more widespread while we move more toward a "smart grid" dominated by renewables and distributed energy resources such as PV and batteries (and soon electric vehicles too!).

Possible examples of tariffs are:

- "Flat": energy price is constant on different hours and days;

- “Time of Use (ToU)”: e.g., day-night tariff, where prices during the night may be lower, or PV-oriented tariffs where prices are much higher during the day for PV customers to prevent them from injecting into the network and incentivise self-consumption to prevent grid issues;
- “Dynamic” tariffs: e.g., prices might change every hour every day, following expected wholesale market prices, and might be communicated with certainty the day before;
- “Real-time” tariffs: e.g., prices might be communicated closer to real-time, so the associated uncertainty might be higher.

Also, tariffs might be “directional”, with prices to buy electricity being different from prices to sell electricity. For example, higher selling prices may be associated with “feed-in tariffs” to incentivize installing PV panels, but might also be lower in some cases, for example to disincentivise power injection.

You are incentivized to look for different tariffs offered by different “retailers”. Start checking your own bill, to start with, and you’ll see that it may not be so simple. For example, you might also be asked to pay a fixed component additionally to energy prices, or a kW-peak component linked to your peak consumption. This is particularly interesting, as it might affect the way you optimize your house consumption.

Moving forward in the future, households might also become part of an aggregation that participate in markets, for example as part of a “virtual power plant” scheme (if interested, you can google the Project EDGE we are currently working on at the University). In some cases the household might be subject to real-time pricing from the aggregator, and these prices might be a pass-through from the wholesale market plus some fixed or dynamic component that is linked to paying network utilization and access fees. On the other hand, they might also directly “bid” their own prices into the market, in the case through an aggregator (how much would you value your PV output?)

Information on wholesale energy prices in Victoria (both current and historical) are available here: https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/data-nem/aggregated-data

Packages and Examples

You may want to use a Python-based environment to implement your HEMS given the wide range of useful packages and libraries available:

- To implement your optimization model, you may want to use the Python-based optimization programming language environment *pyomo* (installation steps and general info can be found here: https://pyomo.readthedocs.io/en/stable/installation.html)

- An MPC package is also available in Python: https://www.do-mpc.com/en/latest/project_structure.html#template-model).

- Other useful packages available in Python, which you may have already seen, are:
    - *numpy*, https://numpy.org/
    - *pandas*, https://pandas.pydata.org/
    - *matplotlib*, https://matplotlib.org/

- Simple examples on how to model the different technologies (solar PV, BESS and EHP) and building, suitable for successive optimization implementation in your project, are provided in a jupyter notebook format (using the *pyomo* optimization environment) that is included in the starter kit folder: Technology_modelling_starter_kit.ipynb

Of course, feel free to use completely different packages and tools such as *Matlab*, if you're more comfortable with them.

Good luck with the project and if you are interested in this kind of application and new schemes where houses with distributed energy resources such as PV, batteries, electric vehicles, etc., will make their own bids to buy and sell energy to the wholesale market, exchange electricity with other households in local communities (the so-called peer-to-peer trading), you should definitely attend the ELEN90092 "Low-Carbon Grids" and ELEN90077 "Grid integration of renewables" courses that we offer in the "Low-Carbon Power Systems" EEE specialization!